NISTIR 4593

(JAPAN TECHNOLOGY PROGRAM)

High Magnetic Field Facilities in Japan Related to Superconductivity Research

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August 1991

This directory was prepared in response to the Japanese Technical Literature Act of 1986. This Act requires the Secretary of Commerce to prepare annual reports regarding important Japanese scientific discoveries and technical innovations in such areas a computers, semiconductors, biotechnology, and robotics and manufacturing.

U.S. DEPARTMENT OF COMMERCE
Robert A. Mosbacher, Secretary
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John W. Lyons, Director

PREFACE

This report is written in partial satisfaction of the requirements of the Japanese Technical Literature Act of 1986, Public Law 99-382 (Aug. 14, 1986). This law requires the Secretary of Commerce to prepare annual reports on the important scientific discoveries and technical innovations in certain important identified areas such as computers, semiconductors, biotechnology, robotics, and manufacturing. This report on the magnetic field facilities in Japan for conducting research on superconducting materials is a result of a trip to various locations in Japan between August 22, 1990 and September 1, 1990 by Dr. Robert Shull, a prominent researcher in both magnetism and superconductivity at the National Institute of Standards and Technology. For comparison to U.S capabilities, Dr. Shull also made trips to the Francis Bitter National Magnet Laboratory at MIT and to the Los Alamos National Laboratory respectively before and after the Japanese trip. The organizations visited in Japan included the High Field Laboratory for Superconducting Materials (HFLSM) at Tohoku University, Osaka University, Sumitomo Electric Industries Ltd., Matsushita Electric Co. Ltd., the National Research Institute for Metals (NRIM) at Meguro, the National Research Institute for Metals (NRIM) at Tsukuba, the Electrotechnical Laboratory (ETL), the International Superconductivity Technology Center (ISTEC), Nippon Telephone and Telegraph Co. (NTT) at Ibaraki, and the Institute for Solid State Physics (ISSP) at the University of Tokyo. The views expressed in this publication are those of the author and do not constitute any official NIST position.

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EXECUTIVE SUMMARY

This evaluation of the high magnetic field facilities in Japan related to superconductivity research was prepared in response to the Japanese Technical Literature Act of 1986 wherein the Secretary of Commerce is required to prepare annual reports regarding important Japanese scientific discoveries and technical innovations in such areas as computers, semiconductors, biotechnology, and robotics and manufacturing. This report was prepared as a result of a trip to the high magnetic field facilities and the centers of superconductivity research in Japan and to the high magnetic field centers in the United States between August and September, 1990. At these organizations, observations were made of the magnetic field capabilities, of advancements being made to improve these capabilities, of the equipment accessibility to outside users, and of the use of their magnets for studying superconducting materials.

The author found that the highest magnetic field capabilities in Japan are presently comparable to the highest elsewhere in the world, for both DC and pulsed fields. Within the next 3 years, however, he judged the Japanese will lead the world for a short time in this area. A concerted effort at the National Research Institute for Metals (NRIM), through the Multi-Core Research Project on Superconductivity of the Science and Technology Agency in Japan, is presently being directed toward the development and construction of very high field and greater homogeneity research magnets. The new magnets are projected to be finished in 1993. One of these new magnets would be capable of creating the highest DC field in the world: 40 Tesla. The present U.S. limit (currently the highest in the world) is 31.8 Tesla (with 35 Tesla to become available in 1991) at the Francis Bitter National Magnet Laboratory (FBNML). The new U.S. National High Magnetic Field Laboratory, soon to be located at Florida State University (Tallahassee) and at the Los Alamos National Laboratory (Los Alamos, NM), plans to have a DC field capability of 35 Tesla by 1995 and a 45 Tesla magnet somewhat later. Consequently, it appears that there will be a short period of time starting in 1993 when the highest DC field research will need to be performed outside of the U.S. For the study of superconducting materials, fortunately, most research does not need the very highest magnetic fields. However, before application of promising new materials by industry, especially those to be used for making even higher field magnets, their critical parameters (critical field, H_C, critical current density, J_C, and critical temperature, T_C) will need to be optimized at the highest magnetic fields. Whether U.S. efforts to develop industrially important superconducting materials are slowed by needing to perform the highest field characterization outside the United States between 1993 and 1996 probably will depend on U.S. budgets in superconductor research and the competition for magnet time from abroad.

There are four major centers of high field activity [Tohoku University (High Field Laboratory for Superconducting Materials, HFLSM), Osaka University (Research Center for Extreme Materials, RCEM), University of Tokyo (Institute for Solid State Physics, ISSP), and NRIM] in Japan compared to only the FBNML (and a small, but soon to be

expanded, effort at the Los Alamos National Laboratory) in the U.S. Consequently, there appears to be more total financial support for these activities in Japan than in the United States. Even so, the four centers of very high field expertise in Japan do not appear to be sufficient to handle their present need since Japanese scientists (even those located at these four organizations) come to the U.S. and actively utilize the FBNML at MIT. Perhaps the reason for this is that FBNML is set up as a user facility (having a support staff), while the Japanese centers are not. In 1993, when the construction of the new magnet facilities at NRIM are completed, it is the intention of the Director General to make it an "international center" wherein outside users are encouraged.

Presently, because there are more centers of high magnetic field expertise in Japan, there is also a greater effort devoted toward researching new materials and improved magnet designs for achieving even higher fields. Consequently, numerous developments in magnet technology have recently been made in Japan. Examples are the large variety of new superconducting materials (e.g. Nb-Ti-Hf and Nb-Ti-Ta wires, higher J_C Nb_3Sn wires, multifilamentary Nb_3Al wires, Ag-sheathed BiPbSrCaCuO high T_C tapes, and the "doctor blade"-prepared YBaCuO high T_C tapes), the construction of composite magnet coils combining various superconductors in different coil regions to maximize the total field capability, the development of submicron filamentary wires with enhanced J_C values, and the characterization of various composite materials (e.g. Cu/Al, Cu/Ag, Cu/Al_2O_3, and Cu/NbTi composites) having enhanced yield strengths without significantly reduced thermal conductivities for use in both pulsed and DC field applications. These advances have also been made despite the fact that, due to the lack of a natural supply of helium gas, in some cases the availability and high cost of liquid helium in Japan has restricted the usage of their magnet systems. In the near future, the short term U.S. effort will be directed toward the construction and staffing of a new magnet laboratory and less toward the development of new materials and designs. Consequently, the near term advances in magnet technology are likely to come from abroad.

The magnetic field facilities in the typical Japanese laboratory investigating superconductors depends on the type of laboratory. Japanese government laboratories were the best equipped (both in terms of equipment age and field capability). In comparison, university equipment was found to be much older and generally less abundant. The author also found that the Japanese industrial laboratories (even those dealing with superconducting materials) possessed only low field capabilities (commonly $<$ 1 Tesla); the industries relying upon interaction with the Japanese high magnetic field centers to obtain the high-field information they need. These research capabilities are comparable to those in United States laboratories. It was also noted that much of the Japanese magnetic field equipment was constructed by companies (e.g. Oxford Instruments, Inc.) outside of Japan.

ABSTRACT

This report describes the high magnetic field facilities presently available in Japan and how those facilities are being used for the study of superconducting materials. Particular attention is devoted to Japanese technological advances in the development of superconducting materials which may have an impact on the construction of future high magnetic field facilities. Both pulsed magnetic field facilities and constant field generation are evaluated. In addition, future facilities to become available in Japan are listed.

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I. INTRODUCTION

A. HISTORICAL BACKGROUND FOR RECENT EFFORTS

In 1987-8 Professors Frederick Seitz (Rockefeller University) and Robert Richardson (Cornell University) chaired a special panel of experts which held an international workshop in July, 1988 to evaluate the scientific opportunities in high magnetic field research and to provide advice on facilities, instrumentation, personnel, and resources that would be needed to carry out such research in the United States. As a result of the workshop, a report[1] was written for the National Science Foundation (NSF) which itemized those improvements in magnetic field capabilities necessary for future scientific advances in many fields, including nuclear magnetic resonance, atomic and molecular physics, plasma physics, biophysics and biosciences, magnetochemistry, superconductivity, metallic superlattices, semiconductors, magnetism, quantum fluids and solids, and polymer science. This report was subsequently used by NSF in 1989-1990 as the basis for soliciting proposals throughout the United States to upgrade the present US capabilities in high magnetic field research through the establishment of a new National High Magnetic Field Laboratory (NHMFL). This new laboratory would develop and operate the following state-of-the-art facilities: (1) a hybrid 45 Tesla DC magnet

having a 32mm bore and using a 20 MW low-ripple power supply, (2) a high homogeneity superconducting magnet for Nuclear Magnetic Resonance (NMR) experiments with fields greater than 25 Tesla, and (3) intense pulsed field facilities capable of producing fields in excess of 75 Tesla for time durations of milliseconds and of 200 Tesla for microsecond durations. The aim was to have the NHMFL operational by 1995.

In 1988 the Science and Technology Agency (STA) in Japan started its Multi-Core Research Project on Superconductivity (MCRPS)[2]. As part of this project, large improvements (corresponding to the future scientific needs listed in the Seitz-Richardson report) were to be made in the high field capabilities in Japan[3]. Similar development efforts sponsored by the Council of Ministers for the European Community of Ministers (EC) also started in Europe in 1989[4].

B. CONSIDERATIONS FOR HIGH MAGNETIC FIELD GENERATION

A magnetic field (H) is generated when an electric current is passed through a conductor. When the conductor is in the form of a loop, the magnetic field will be directed along the axis of the loop. The larger the current, the larger will be the magnetic field generated. To a certain extent, the cost of power and the ability of the local power company to provide current puts a limit on the maximum field possible. Another factor limiting the

maximum field achievable by a current loop is the heat generated in the conductor due to its electrical resistance. Since the resistance of most metals increases with increasing temperature, more heat is generated per unit time the longer the current flows. Consequently, significant external cooling is required in order to keep the conductor from heating to the point where it melts or falls apart. Resistive magnets are presently available which provide magnetic fields on the order of 25 Tesla. High field DC magnets can also be constructed using superconducting materials (which possess zero resistance to a DC current) for the windings. Since there is no power loss due to resistive heating using these materials the total power supply cost is lowered. However, magnets using superconductor windings will still be upper-field limited by the critical field (H_C) values of the superconductor. When H exceeds H_C the material loses its superconducting property and develops a resistance. At 4.2 K the highest superconducting magnet field is 18.1 Tesla[5], provided by a magnet at NRIM. The highest DC magnetic fields are generated in hybrid systems wherein a water-cooled resistive conductor magnet is placed inside the bore of a superconducting magnet. Presently, the highest field DC magnet is located at the Francis Bitter National Magnet Laboratory (FBNML) at MIT (Cambridge, MA) and is capable of providing a 31.8 Tesla field in a 33 mm diameter bore[4]. Other high field DC magnets of similar strength are the 31.4 Tesla magnet at the High Field Magnet Laboratory at CNRS in Grenoble, France[6], the 31.1 Tesla hybrid magnet at the High Field Laboratory for Superconducting Materials (HFLSM) at Tohoku University in Sendai, Japan[7], and the 30.4 T magnet at the University of Nijimegen in Nijimegen,

Netherlands[8].

Higher magnetic fields than 31.8 Tesla may be obtained for short times by pulsing the current[9] or by quickly compressing magnetic flux[10] into small volumes. The magnitudes of the fields achievable by both of these techniques are limited by similar considerations described above for the DC fields. In addition the maximum field is limited by the power supply available and by how fast the current can be transferred into the magnet winding. Since both these techniques require a large change in magnetic flux per unit time, significant eddy current heating will occur and the cooling considerations become more significant. In this application superconducting conductors are not useful since they are not resistanceless under pulsed current conditions. At the very high fields created by the pulsed techniques, the forces exerted on the conductor by the passage of the electrical current also become particularly important. This force (which is in a radial direction for a current loop) increases as H^2, thereby limiting the magnitude of the maximum achievable field by the tensile strength of the conductor[4]. Consequently, for the generation of pulsed fields the ultimate tensile strength (UTS) and the electrical conductivity (σ) of the conductor both need to be maximized. In the United States the centers of high pulsed magnetic field activity are the Francis Bitter National Magnet Laboratory (pulsed current systems)[11] and the Los Alamos National Laboratory (explosive flux compression)[12].

C. HIGH MAGNETIC FIELD APPLICATIONS TO SUPERCONDUCTIVITY

Superconductors are involved in high magnetic field research in two respects: (a) as the conductor material used to generate the high DC magnetic fields required for the research and (b) as the material under investigation requiring high magnetic fields. Of course much of the motivation for the efforts under category (b) is driven by the requirements for utilizing the material under category (a). Superconductors are characterized by three basic parameters: the critical temperature, T_C, the critical field, H_C, and the critical current density, J_C. If any of these critical values is exceeded, the material loses its superconducting state and develops a non-zero electrical resistance. In general, each of these critical values is a function of the values of the other two variables. H_C and J_C are zero at the critical temperature and both increase as T decreases below T_C. At any given temperature below T_C, J_C will depend on the value of any applied field (H) and H_C will depend upon the value of any electric current passing through the material[13]. In addition, all three critical parameters will also depend on the presence of any mechanical stress[14]. The manner in which the values of all these parameters are interconnected is very important for determining the operational limits of the superconductor. In 1986 a new class of superconductors, based on ceramic oxides, was discovered by Bednorz and Müller[15] which possessed very high transition temperatures ($30\,K < T_C < 130\,K$). There have been great expectations for the future application of these new materials, especially at temperatures higher than presently possible with the previously known

superconductors. However, these expectations have not been realized yet, in large part because of the unfavorable relationships so far found between T_C, J_C, and H_C in these materials[16].

D. REPORT ORGANIZATION

This report is organized according to research areas. Many activities are occurring simultaneously in the various laboratories in Japan both in terms of magnet development and superconducting materials research. The first part describes the activities pertaining to the development of high magnetic field facilities and lists the general magnetic field equipment available for research at the average laboratory in Japan. The second part is a description of the research methods used in Japan for studying superconducting materials at high magnetic fields.

II. HIGH FIELD MAGNET DEVELOPMENT

At each high magnetic field facility in the world, a certain amount of the total effort is directed toward research on creating even higher magnetic fields. The very high field facilities in Japan[17] include the High Field Laboratory for Superconducting Materials (HFLSM) at Tohoku University[7], the Research Center for Extreme Materials (RCEM)

at Osaka University[18], the National Research Institute for Metals (NRIM) at Meguro and at Tsukuba[3], and the Institute for Solid State Physics (ISSP) at the University of Tokyo[19]. By comparison there is only one major facility in the U.S. devoted to high magnetic field research: the Francis Bitter National Magnet Laboratory at MIT[20]. Consequently, in the absence of any major government project to improve magnet capabilities there has historically been a larger total effort in Japan devoted to the development of higher magnetic fields than in the U.S. However, since 1988 there has been an increase in the already significant Japanese effort through the Multi-Core Research Program on Superconductivity (MCRPS) of the Science and Technology Agency in Japan[2]. The majority of this increased effort is being performed at NRIM (both at Meguro and Tsukuba). By 1993 the Meguro facilities of NRIM are expected to be moved to Tsukuba.

A. NRIM FACILITIES

The aims at NRIM (Tsukuba) are the construction of (1) an 80 T class long-pulsed (several milliseconds) magnet, (2) a 20 T class large-bore (50 mm diameter) DC superconducting magnet, and (3) a 40 T class hybrid magnet, all to be completed by 1993. Items (2) and (3) are presently under construction by Japanese industry with close consultation with NRIM scientists. NRIM welcomes outside users (generally has ~8 international guest scientists each year spending up to 6 months at NRIM), has

several scientists spending time working in the U.S., and in fact plans to name its high field facility an "international center" upon its completion in 3 years.

(1) 80 T, Long-Pulse Magnet

The 80 T, long-pulse (several milliseconds) magnet under development at NRIM (Tsukuba) will use a new capacitor bank (completed in June, 1989) having a stored energy of 1.6 MJ, capacitance of 128 mF, and a maximum voltage of only 5 kV[3]. This maximum voltage, which is about ten times smaller than for normal power supplies, allows higher field generation because the insulation between coils in the helical magnet winding can be reduced. A particular innovation at NRIM regarding this magnet is the use of conductor coils made of Cu having fine filaments of Ag. This type of material (a composite using fine filaments of a second phase aligned inside the matrix material) was first used by Foner[21] for making conductor coils at the Francis Bitter National Magnet Laboratory in 1988. In that case fine filaments of Nb were dispersed in a Cu matrix. Such composites are advantageous since they possess only slightly lower electrical and thermal conductivity than pure Cu, but much higher tensile strengths. The Cu/Ag (containing 10-30 atomic percent Ag) multifilamentary material, however, appears to be even better than the Cu/Nb composites: both have tensile strengths (at 0.2% strain) on the order of 100 kg/mm^2, but the thermal conductivity of the Cu/Ag composite is near 80% that of pure Cu compared to the 60% value for the Cu/Nb composite. For the

largest fields, this magnet is designed to be operated with the magnet coils immersed in liquid nitrogen similar to the FBNML system which presently holds the record of 68.4 T for a pulse duration of 5.6 msec[4]. Composites of Al_2O_3 dispersed in Cu (figure 1) are also being studied at NRIM for use as the electrical conductor. For safety, the test facility for these experimental high-field coils is located inside a special steel chamber housed inside a separate room (see figure 3, reference 3) from the operator. Cross sections of several test coils are shown in figure 2.

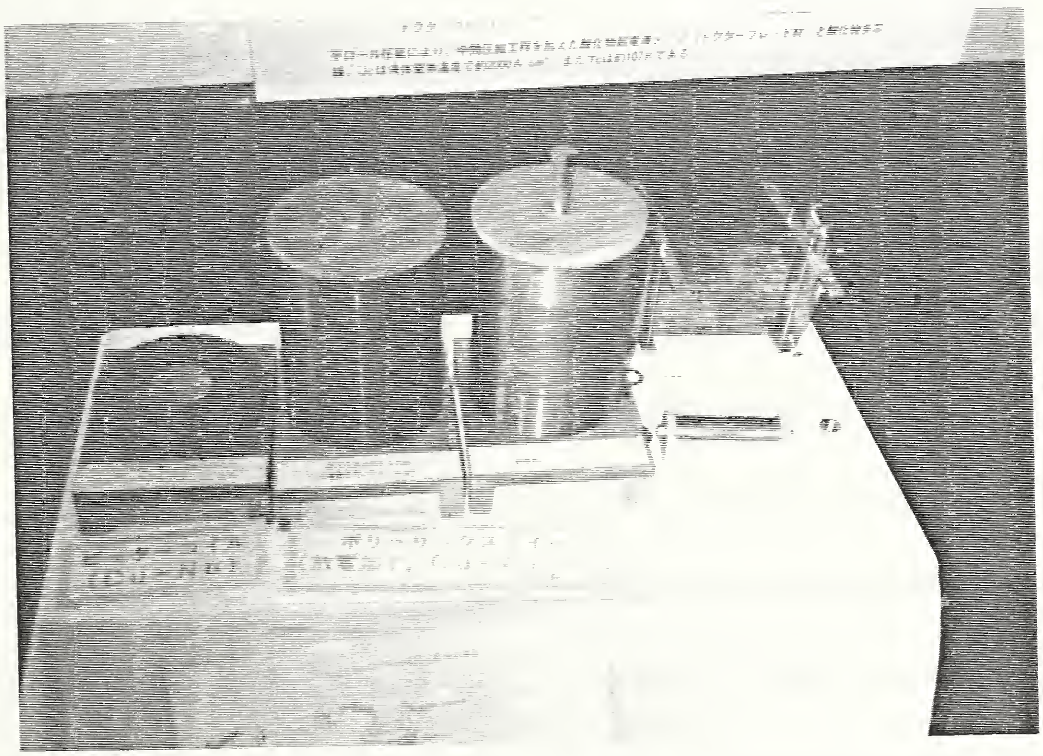


Figure 1. Multiturn magnet coils of two different experimental conductors being studied at NRIM for use in construction of a several-millisecond, pulsed-field magnet.

Figure 2. Cross sections of several magnet coils plus one complete coil (upper right) being studied at NRIM for use in construction of a several-millisecond, pulsed-field magnet.

(2) Large Bore, 20 T Superconducting Magnet

The large bore (50 mm diameter) 20-T DC superconducting magnet is being constructed using four concentric coils[3] operated at 1.8 K. The innermost coil is a multifilamentary (Nb, Ti)$_3$Sn conductor prepared by the "Nb-tube" method; the second innermost coil (176 mm bore) is made of a multifilamentary (Nb, Ti)$_3$Sn conductor prepared by the "bronze" process; the 3rd coil (376 mm bore) is also a multifilamentary (Nb, Ti)$_3$Sn conductor prepared by the "bronze" method; and the outermost coil (795 mm bore) is a multifilamentary conductor made of NbTi. The inner two coils have separate power

supplies while the outer two coils use the same power supply. The innermost coil (which provides a field of 2 T) may also be withdrawn and the magnet operated at 18 T with a bore of 110 mm. This facility will allow high-field characterization of small superconducting coils, strain effect measurements on superconducting materials at high fields, and the evaluation of large size superconductors. Completion is expected in 1993.

(3) 40 T, Hybrid DC Magnet

The highest steady field will be created in a hybrid resistive plus superconducting magnet[3]. The 14 MW water-cooled resistive portion is a polyhelix design (30 mm bore) containing 15 layers and generating a field of 25 T. The outer 15 T superconducting magnet (400 mm bore), designed for operation at 4.2 K, surrounds the resistive magnet and will be constructed of a series of 100 pancake-type coils. Each of these superconducting coils possesses an inner section of multifilamentary $(Nb, Ti)_3Sn$ embedded in either Cu or Cu containing tape-shaped strips of Al. The outer section is made of mutifilamentary NbTi embedded in Cu. Particularly innovative here is the addition of Al tape to the conductor material comprising the innermost region of the coils. It was found that this tape stabilized[3] the superconducting filaments against premature quenching and resulted in a large reduction in the required superconductor weight and of the stored energy in the superconductor. Toshiba Corporation aims to complete construction in 1993.

(4) High Resolution Superconducting Magnets

In addition, two high-resolution high-field superconducting magnets are being installed at NRIM (at Meguro) for de Hass-van Alphen, dHvA, (figure 3) and broad band solid state NMR (figure 4) measurements respectively. Both of these magnets use a combination of Nb_3Sn (inner coils) and NbTi (outer coils) for the conductor material.

(a) (b)

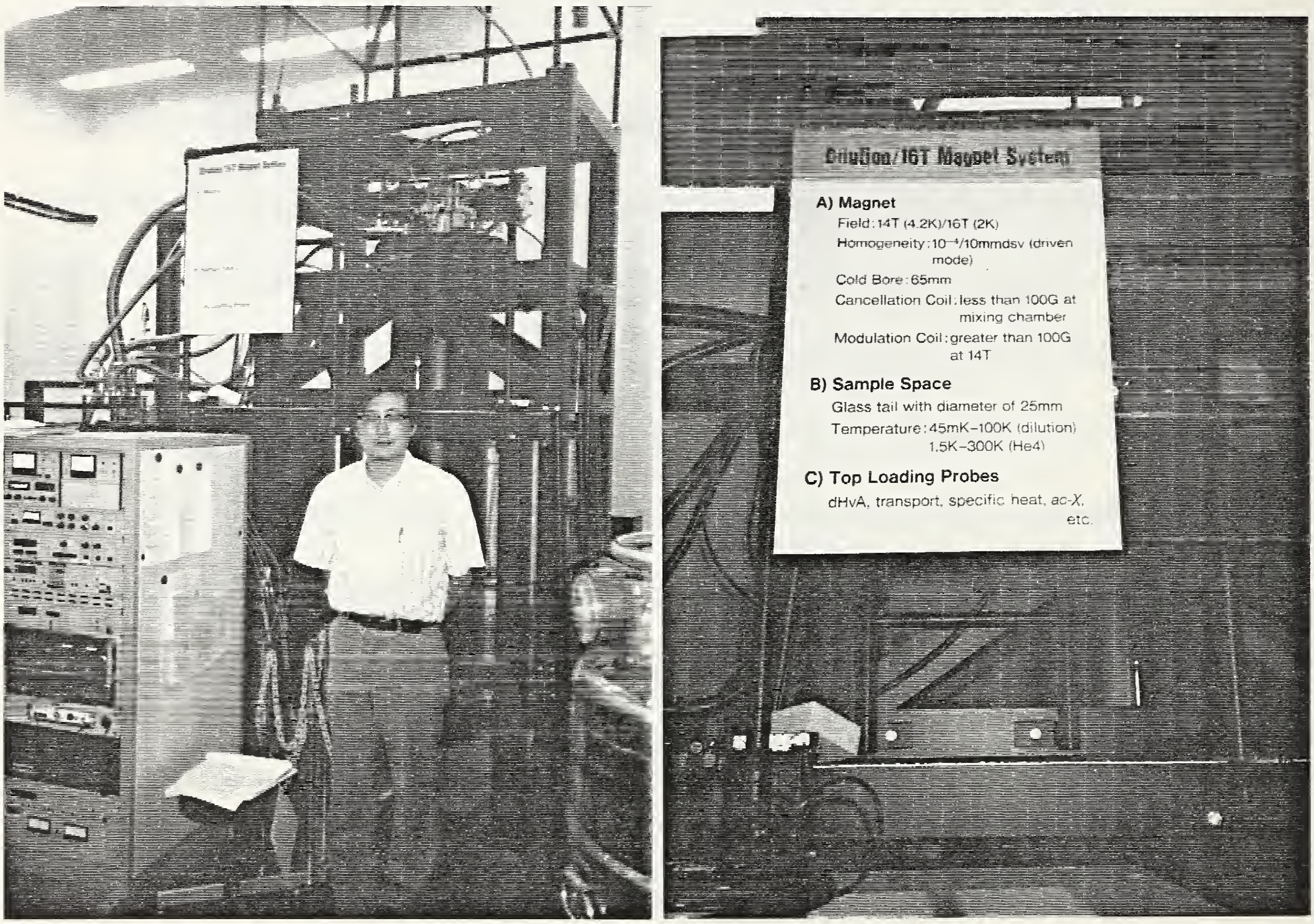


Figure 3. (a) Picture of Dr. Haruyoshi Aoki (Group Head, 1st Laboratory, NRIM, Meguro) standing in front of the new 16 Tesla, high-homogeneity dHvA superconducting magnet having the specifications listed in (b).

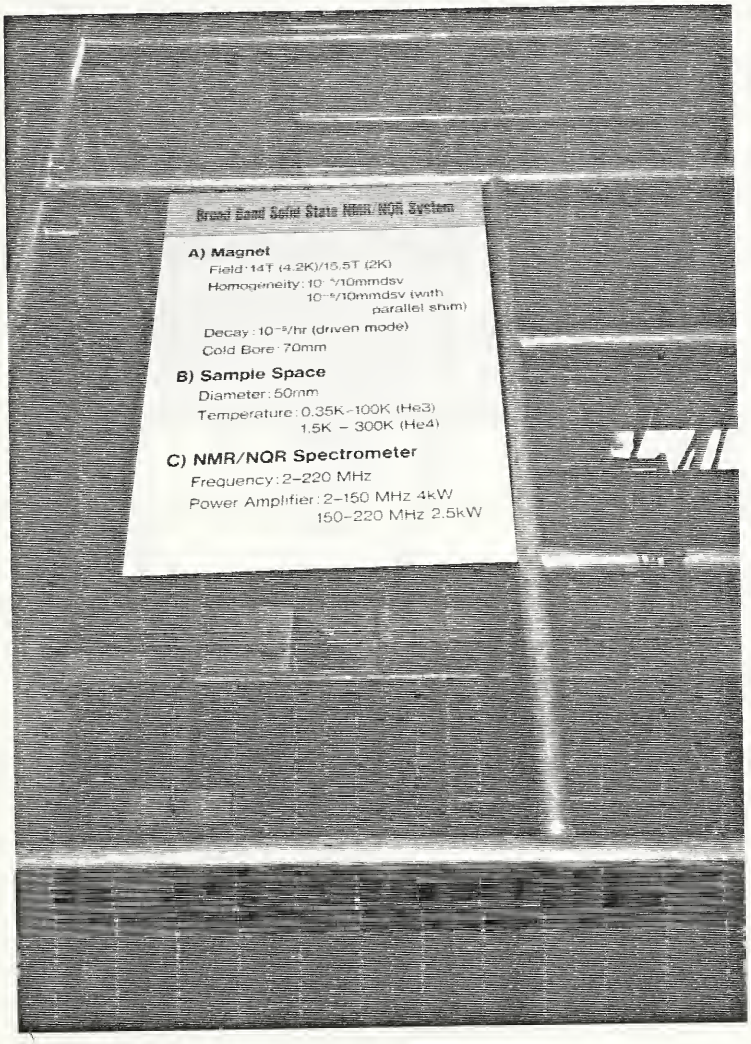


Figure 4. Specifications for the new 14 Tesla broad-band, solid-state NMR superconducting magnet to be installed inside the scaffolding in September, 1990.

The 16 Tesla dHvA magnet (which was originally specified to be designed for only 14 Tesla) has a 65 mm bore, a 10^{-4} field homogeneity, and the special design feature of containing a dilution refrigerator that allows the insertion and removal of samples from the top of the magnet-cryostat assembly. This latter feature makes it much easier and quicker to change samples. This magnet was constructed by Oxford Instruments, Inc. (Oxford, England) and delivered in June, 1990. The 14 Tesla (design specification)

broad band solid state NMR magnet (89 mm bore, 10^{-6} field homogeneity) was also constructed by Oxford Instruments and during my visit to NRIM was being tested by JEOL Ltd. (Tokyo, Japan) along with the NMR electronic detection and analysis system JEOL built for this apparatus. Delivery of the complete system was expected in September, 1990. I was informed that preliminary test data using this system for probing the Cu-atom sites in the near-superconducting compound $YBa_2Cu_3O_6$ indicated peak widths "much narrower" than some of the best NMR data in the world. The narrowness of the NMR peak is a measure of the resolution of the equipment and therefore of the precision for determining the electric field gradient and magnetic field present in the vicinity of the species being probed. Both systems are capable of measurements from 300 K down to 0.35 K.

B. TOHOKU UNIVERSITY FACILITIES

There are presently 3 hybrid magnet systems at the High Field Laboratory for Superconducting Materials (HFLSM), which is part of the Institute for Materials Science (IMR), at Tohoku University: HM1 (figure 5) having a maximum field capability of 31.1 T (32 mm bore), HM2 having a capability of 23 T (52 mm bore), and HM3 with a maximum field of 20.5 T (32 mm bore)[7,22]. The superconducting magnets of HM2 and HM3 are constructed of mutifilamentary NbTi while that of HM1 is a graded combination of multifilamentary Nb_3Sn inner coils and NbTi outer coils. A closed-cycle, deionized-

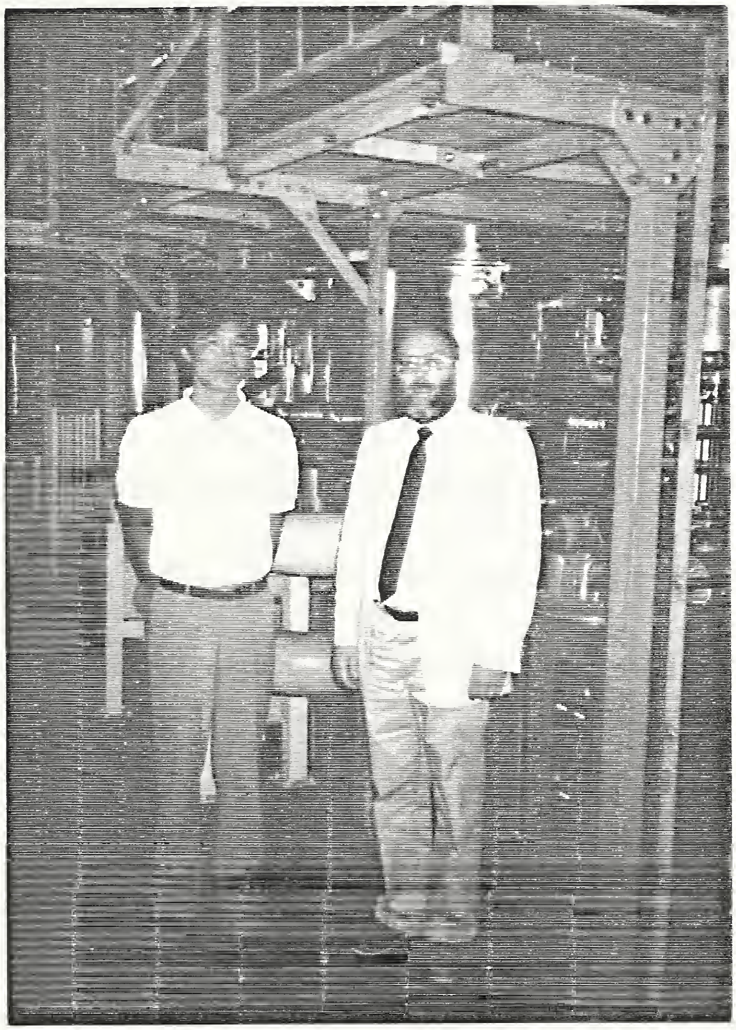


Figure 5. Professor Kazuo Watanabe (left) and the author standing in front of the 31.4 Tesla hybrid magnet at the HFLSM, Tohoku University.

water cooling system with two turbo-refrigerators and cooling towers allows operation of the hybrid magnets even during the summer in contrast to river-water cooled systems. In addition, this facility possesses a large capacity (100 liter/hour) helium liquefier and refrigeration (225 watts cooling at 4.5 K) system. Since all of Japan's helium is imported, liquid helium is expensive and its availability sometimes limits the operating time of Japan's magnet facilities. Even though great amounts of liquid helium are needed

to operate the hybrid magnets at Tohoku University (e.g. near 3000 liters for cooling and operating HM1 for 5 days[22]), the closed cycle liquefier/refrigeration system has sufficient capacity to allow significant periods of operation. The majority of the efforts at HFLSM are devoted toward characterization of superconducting materials. In addition to large current supplies (1500 ampere capability) for use in determining critical currents at high magnetic fields, there are many specialized measurement systems available, including Mössbauer spectroscopy, magneto-optical measurements, and magnetization data. Especially significant is the presence of a 9 Tesla, split-type superconducting magnet combined with a tensile testing machine (500 kg load capacity at 4.2 K) for determining the low-temperature, high-field stress effects on the critical parameters of superconducting materials[23]. Efforts to improve the superconducting characteristics of NbTi have included studies on the effects of third constituent additions like Ta and Hf[24]. Improvements in J_C and H_C were greater for the Nb-Ti-Hf alloys than for the Nb-Ti-Ta materials, probably because some of the Ta was found to precipitate out of solution. The Nb-Ti-Hf alloys were found to be more ductile than NbTi (thereby making them easier to fabricate into coils), and although the transition temperature was reduced slightly from that of the binary NbTi compound by the addition of Hf, the critical field at 4.2 K was increased 20% to 13 T by the Hf addition. Efforts are now underway to improve the highest field capability at HFLSM to 35 T through the construction of another hybrid magnet using perhaps Nb_3Al (which has higher J_C, H_C, and T_C values than does Nb_3Sn, see figure 6) for the superconducting conductor.

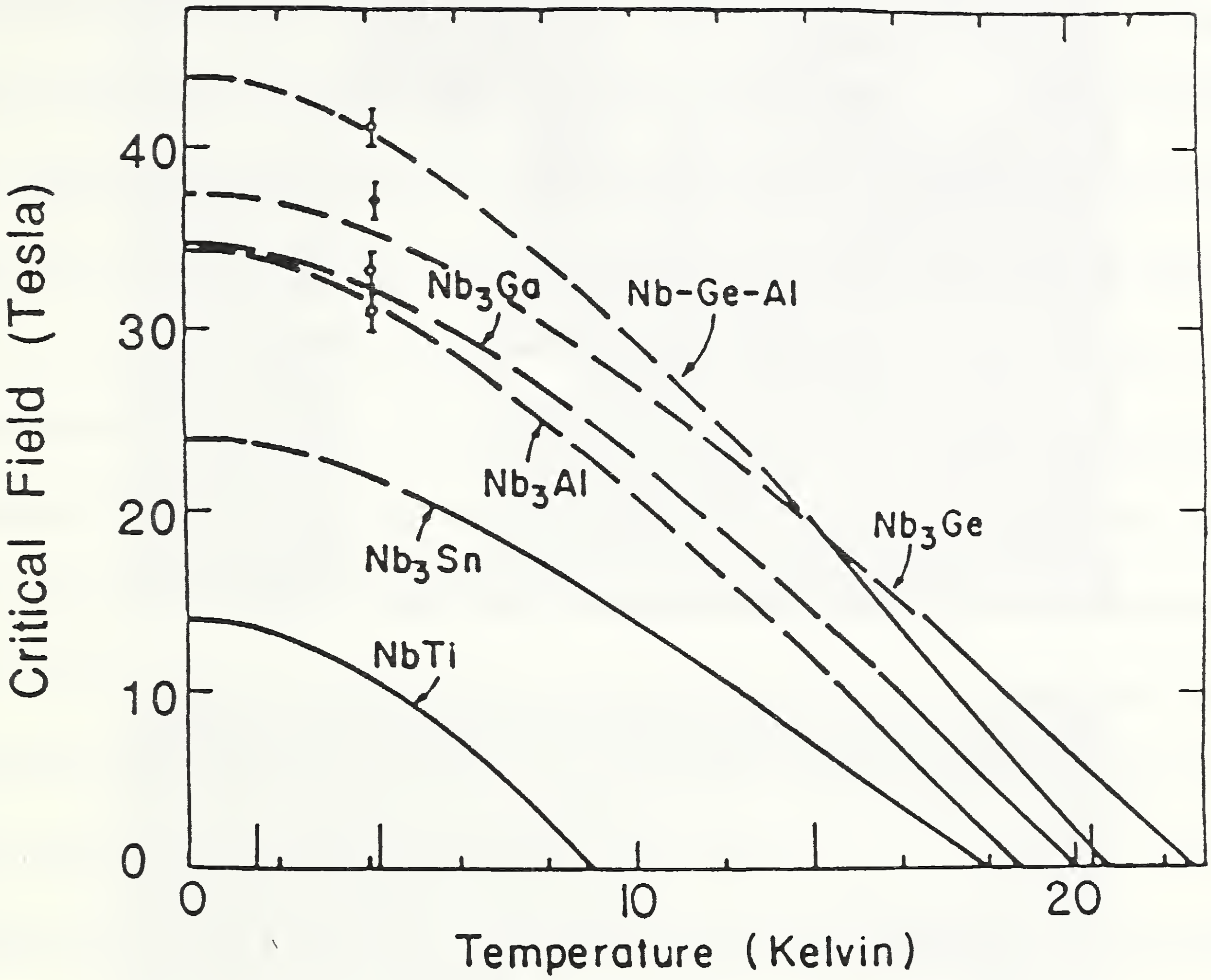
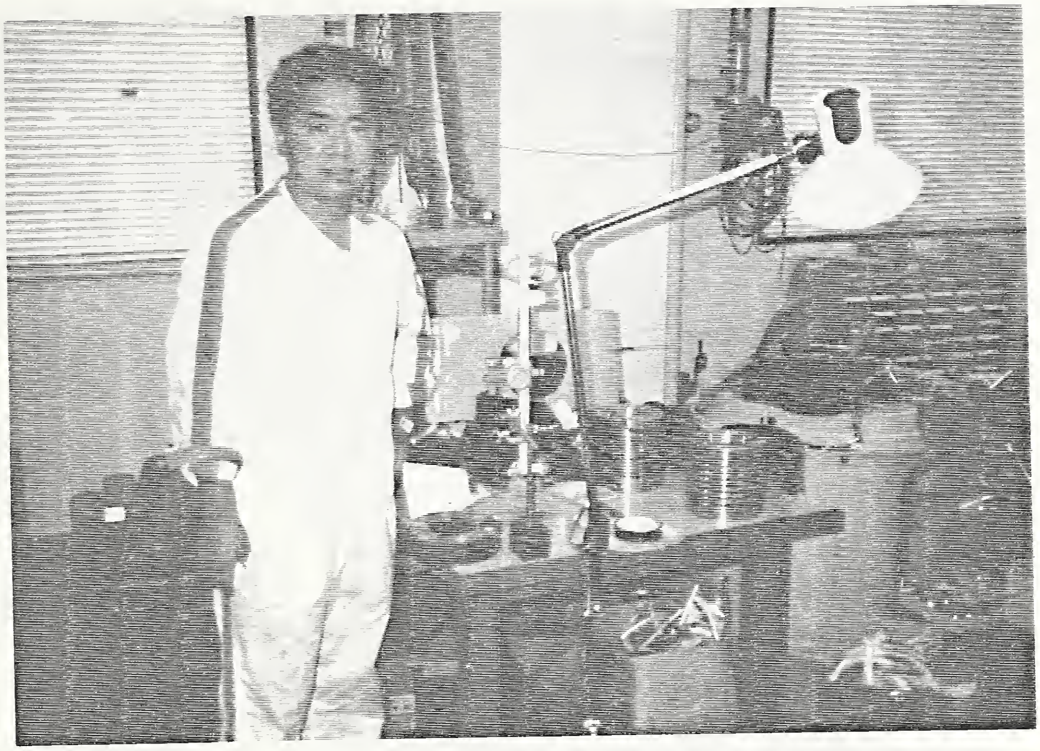


Figure 6. Temperature dependence of the upper critical field (H_{C2}) for several superconducting materials, from Schwartz[25], indicating the respective regions of stability for the superconducting state. The material is superconducting if the combined values of H and T fall in the area below its indicated line.

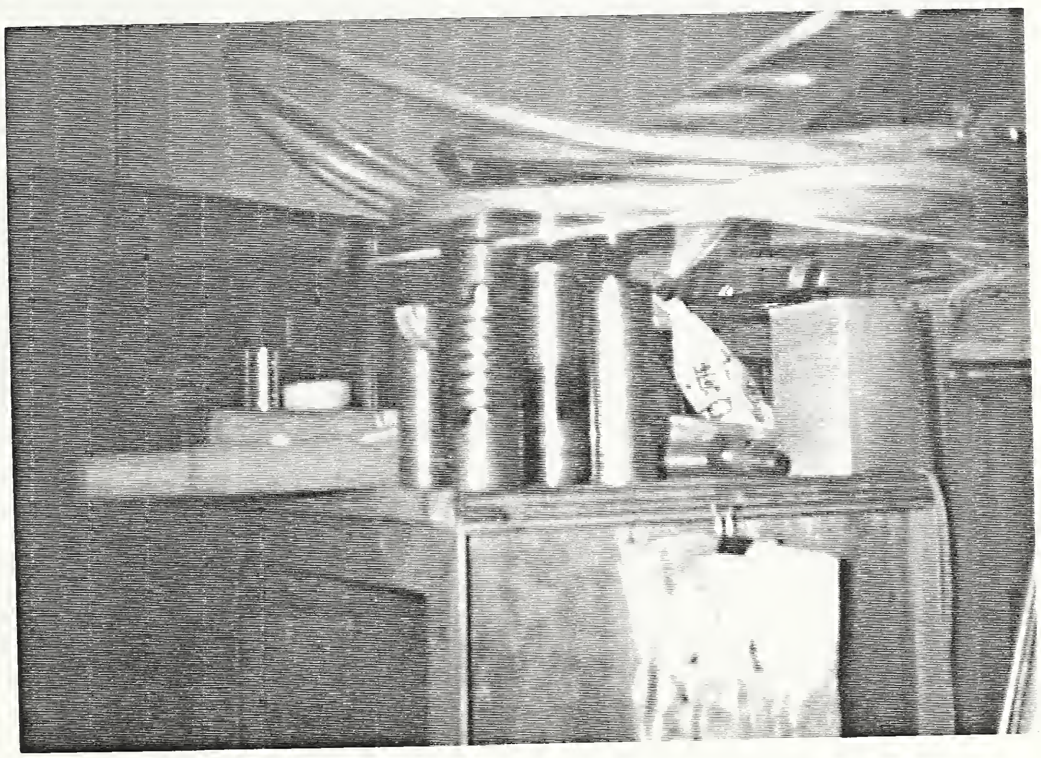
C. OSAKA UNIVERSITY FACILITIES

Since 1973 high-magnetic-field research has been conducted at Osaka University. Particular emphasis has been directed toward research using non-destructive pulsed

magnetic fields[18, 26, 27]. In 1988 a new laboratory (containing a 1.5 MJ, 20 kV, 7.5 mF capacitor bank) was constructed for this research in the Research Center for Extreme Materials (RCEM). The generation of fields to 60 T (for several milliseconds in a 6 cm bore) is accomplished by discharging a capacitor bank into a helical conductor coil machined from a solid block (usually of maraging steel). For fields near 80 T (generated in a 5 mm bore), up to three concentric coils are used (wired either in series or used separately with parallel capacitor banks)[18]. These fields may be applied several times before changing coils or insulators. In the 17 years of operation of this laboratory considerable effort has been devoted to the design and construction of coils for achieving high pulsed fields. For instance, in order to reduce stress concentrations near the conductor ends, which limits the strength of the coil, a special geometry, as shown in figure 7, was found to be beneficial. Also, for nested coils, it is found that each coil needed to be machined with a different pitch[28]. While the outer two coils of the highest field (80 T) magnet are prepared from maraging steel, the innermost coil (6 mm ID and 19 mm OD) is made of five concentric (four turns each) thin (0.2 mm thick by 2 mm wide) Cu-Cr-Zr alloy (?) strips wired in parallel[18]. Research on improvement of the insulator material located between each turn of the coil has resulted in thinner insulators and increased maximum field capability due to increased number of turns per unit length of coil (see figures 8 and 9). Presently an epoxy resin reinforced with glass and Kevlar* fibers is used[18]. External clamping of the outer coil inside a strong steel support is a recent direction of study. For safety reasons, during operation the coils are usually

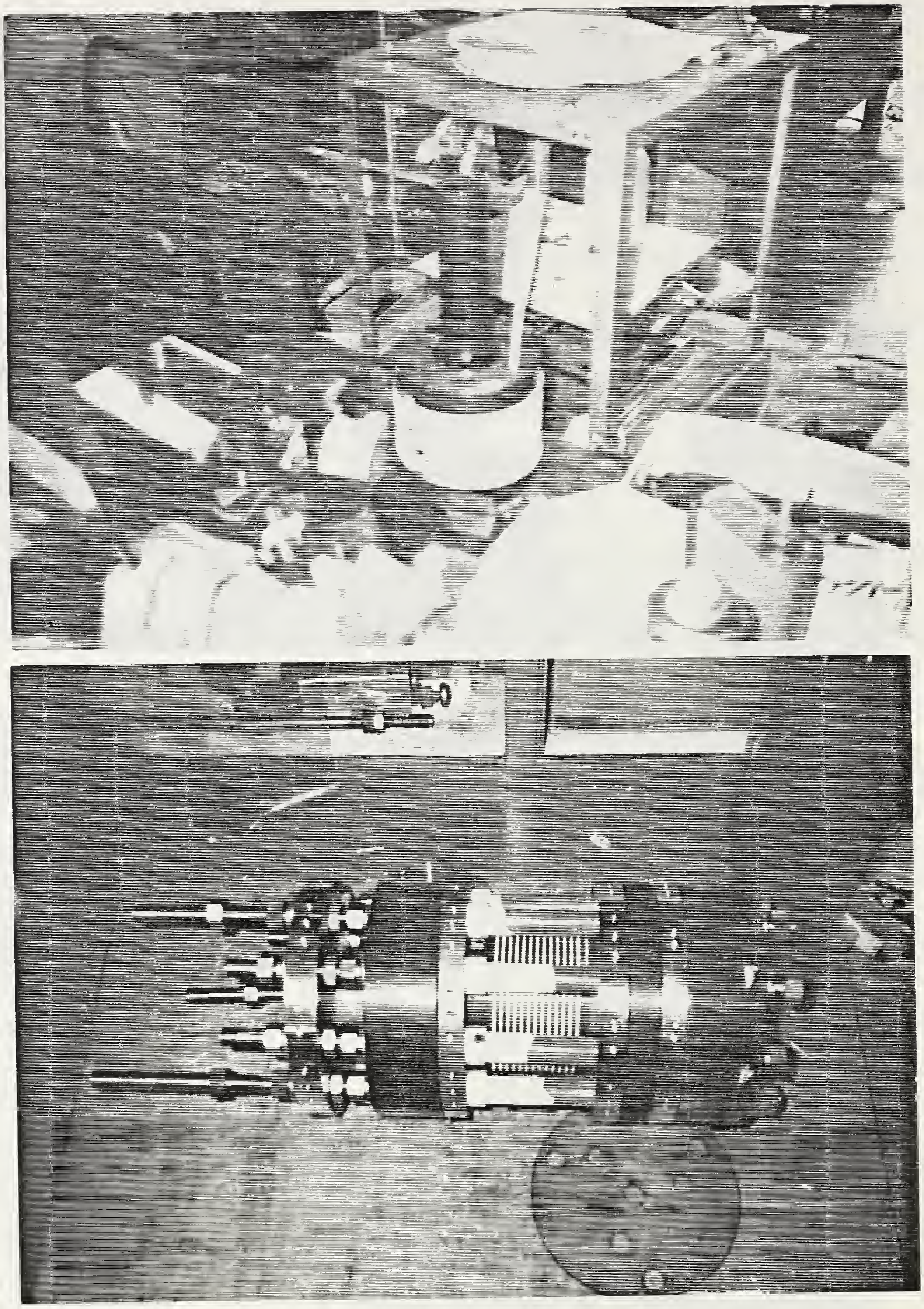


(a)



(b)

Figure 7. (a) Dr. A. Yamagishi standing next to a table supporting two machined large-diameter maraging steel outer coils and (b) several machined smaller-diameter inner helical coils used in Professor Date's high field laboratory at Osaka University.



(a)

(b)

Figure 8. Two nested high magnetic field coils (a) sitting loose on the table top and (b) mounted inside support housing at RCEM, Osaka University. Items apparent in (b) include the current leads (tubes sticking out the left side), insulating supports (white horizontal rods) holding the coil apart, coil insulator sheets (centered vertical white lines between coil windings), and the bakelite supporting structure (wide dark vertical plates at both ends).

placed inside a steel chamber (figure 9), thereby preventing fragments of an exploding defective coil from flying away.

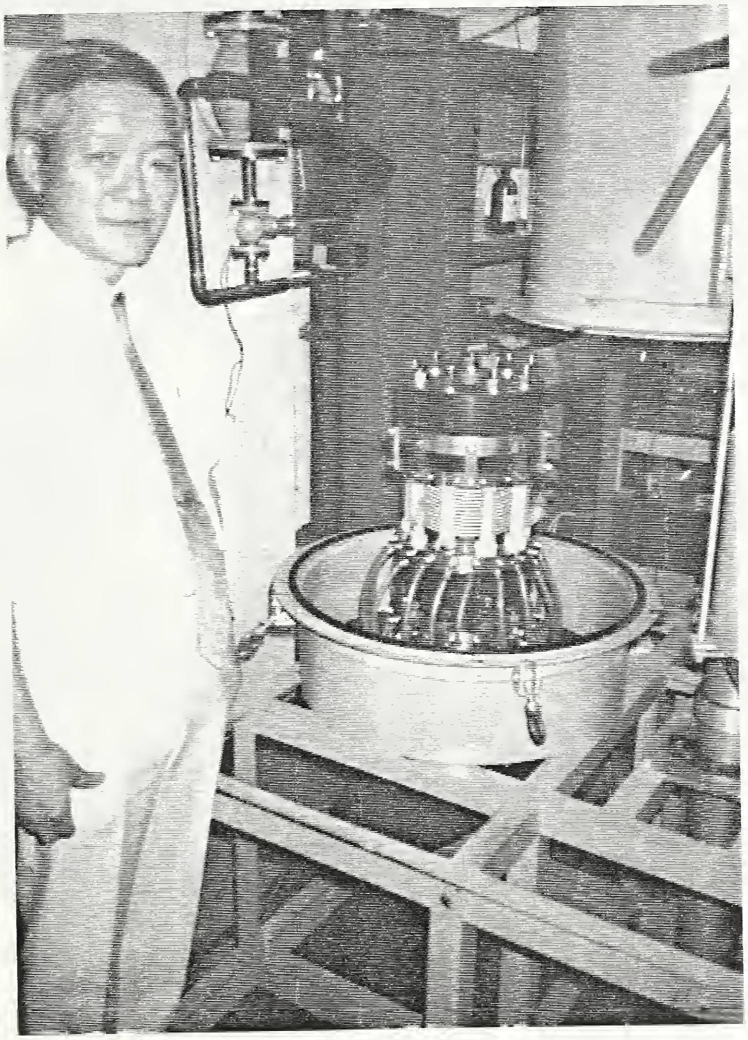


Figure 9. Two nested high magnetic field coils mounted inside containment chamber next to Professor M. Date in preparation for field pulsing at RCEM, Osaka University.

In addition to high field creation, significant effort has been directed at RCEM toward development of fast measurement techniques using these pulsed-field facilities. The basic measurement, that of the magnetic field as a function of time, is made by measuring the voltage induced in a single-turn coil located near the sample. Methods for measuring

magnetization (voltage induction in two coils wired in series opposition, one surrounding the sample), electrical resistivity (usual four-terminal technique), electron spin resonance (using a far-infrared laser and a Ge-In detector), magneto-optic spectroscopy (using a pulsed dye laser and an optical multichannel analyzer), and both the magneto-optic Faraday effect and the Cotton-Mouton magnetic birefringence effect (using a He-Ne laser and a PIN photodiode) have also been developed[27]. This facility operates throughout the year and is open to users from all around the world.

D. UNIVERSITY OF TOKYO FACILITIES

In the megagauss laboratory of the Institute for Solid State Physics (ISSP) at the University of Tokyo a major effort has existed since 1970 toward the generation of pulsed megagauss ($H > 100$ T) magnetic fields[19]. High magnetic fields (up to 385 Tesla for a few microseconds) are generated by quickly compressing the magnetic flux inside a large area into a very small region[29] similar to the effort at the Los Alamos National Laboratory (LANL)[12]. At LANL flux compression is achieved by explosively forcing two conductor plates together in such a way as to force the magnetic flux contained therein toward the apex of the two plates (figure 10). At ISSP the flux compression is accomplished by discharging a large capacitor bank (originally 285 kJ, 30 kV capacity) through a large, single-turn coil, inducing eddy currents in a separate, highly-conducting inner liner. A large, inward-directed electromagnetic force is consequently exerted on

(a) (b)

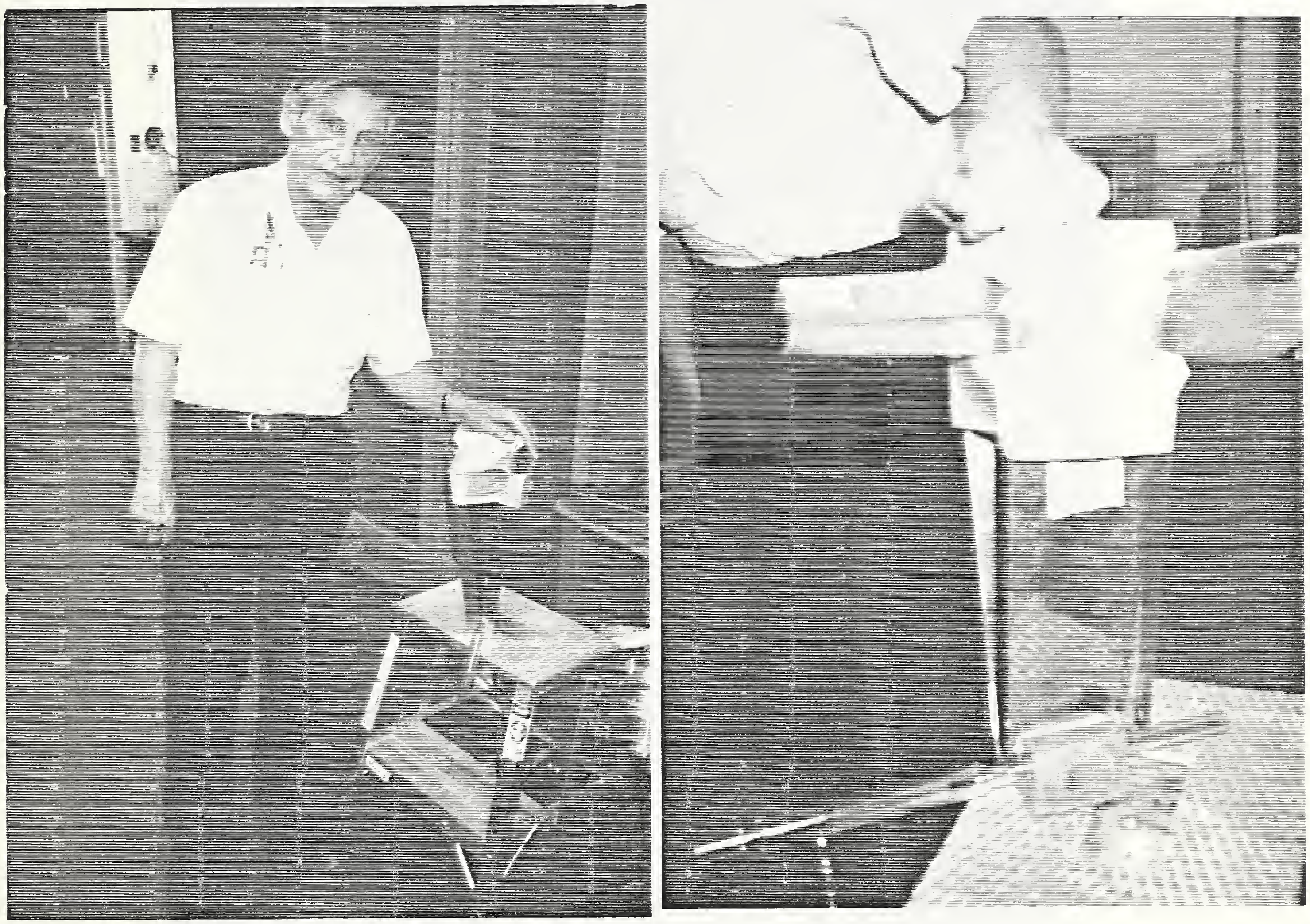
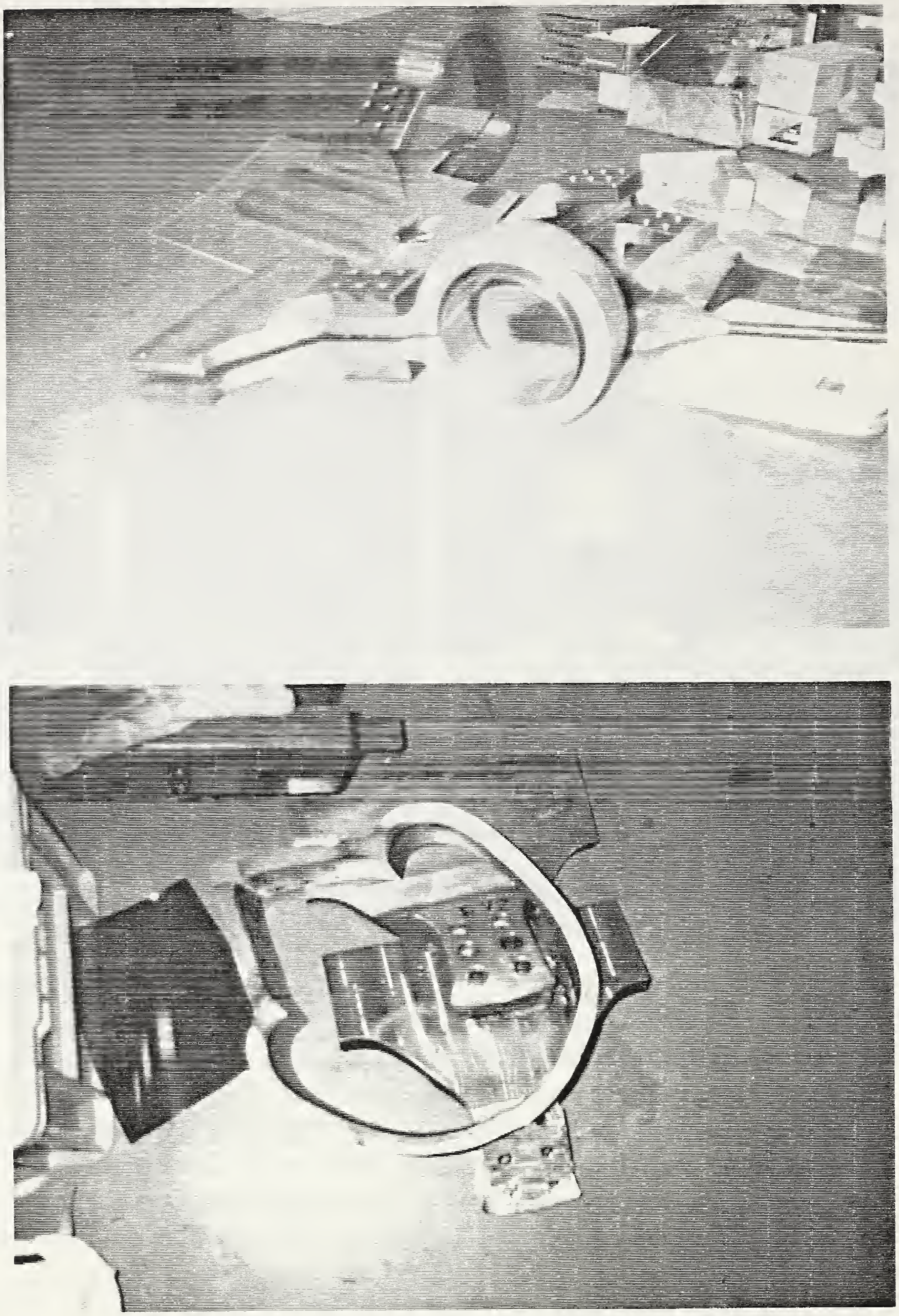


Figure 10. Dr. M. Fowler holding a flux compression wedge of his design for achieving high magnetic fields at the Los Alamos National Laboratory. Operation of the device consists of packing explosive charges on the outside of both vertical members, injecting a magnetic field inside the wedge, and exploding the charges to drive both vertical members together. The sample, located near the apex of the wedge inside the cryostat tube shown in (b), would be destroyed during the microsecond field application.

the liner which causes it to close on itself, thereby compressing the magnetic flux previously injected through the liner (figure 11). In this process both the coil and the sample are usually destroyed as can be seen in figure 11(b). In 1982 a new building was



(a)

(b)

Figure 11. High magnetic field, single-turn primary coil (thick outer aluminum ring) with inner (copper) liner (a) before and (b) after microsecond field application at Professor N. Miura's laboratory in ISSP, University of Tokyo.

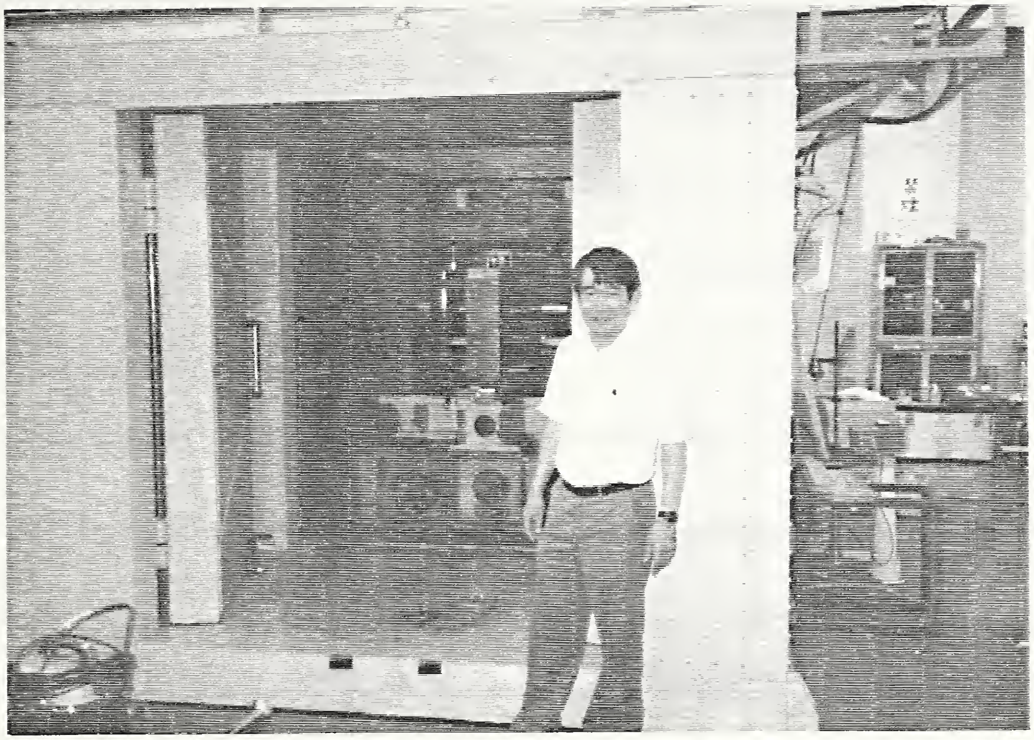


Figure 12. Professor N. Miura standing next to the containment chamber holding the coils, sample, and measurement devices during the field application at ISSP, University of Tokyo.

completed for this work and a much larger, 5 MJ (40 kV) capacitor bank was installed. A recent analysis of the distribution and time dependence of magnetic fields created this way[29] has shown that the longer the inner liner, the more homogeneous is the magnetic field. This method, however, is expensive (primarily, because of machining costs) and there is a long time between uses. A second cheaper method has also been perfected at ISSP for generating somewhat lower fields (100-276 Tesla, for ~3 microseconds), but which does not destroy the sample. In this apparatus the capacitor bank is discharged into a single-turn, small-diameter (2-3 mm) copper coil without a liner. A large internal field is generated until the coil breaks from the radially directed electromagnetic force on it. An especially interesting result of a recent ISSP analysis[29] of this method is that

current still flows in the loop after the coil breaks (presumably through the plasma created during the explosion)! Since the coil explosion is directed outward, the sample is saved. The coil, however, must be replaced each time. For both of these methods, the experiment is conducted inside a large steel chamber (figure 12).

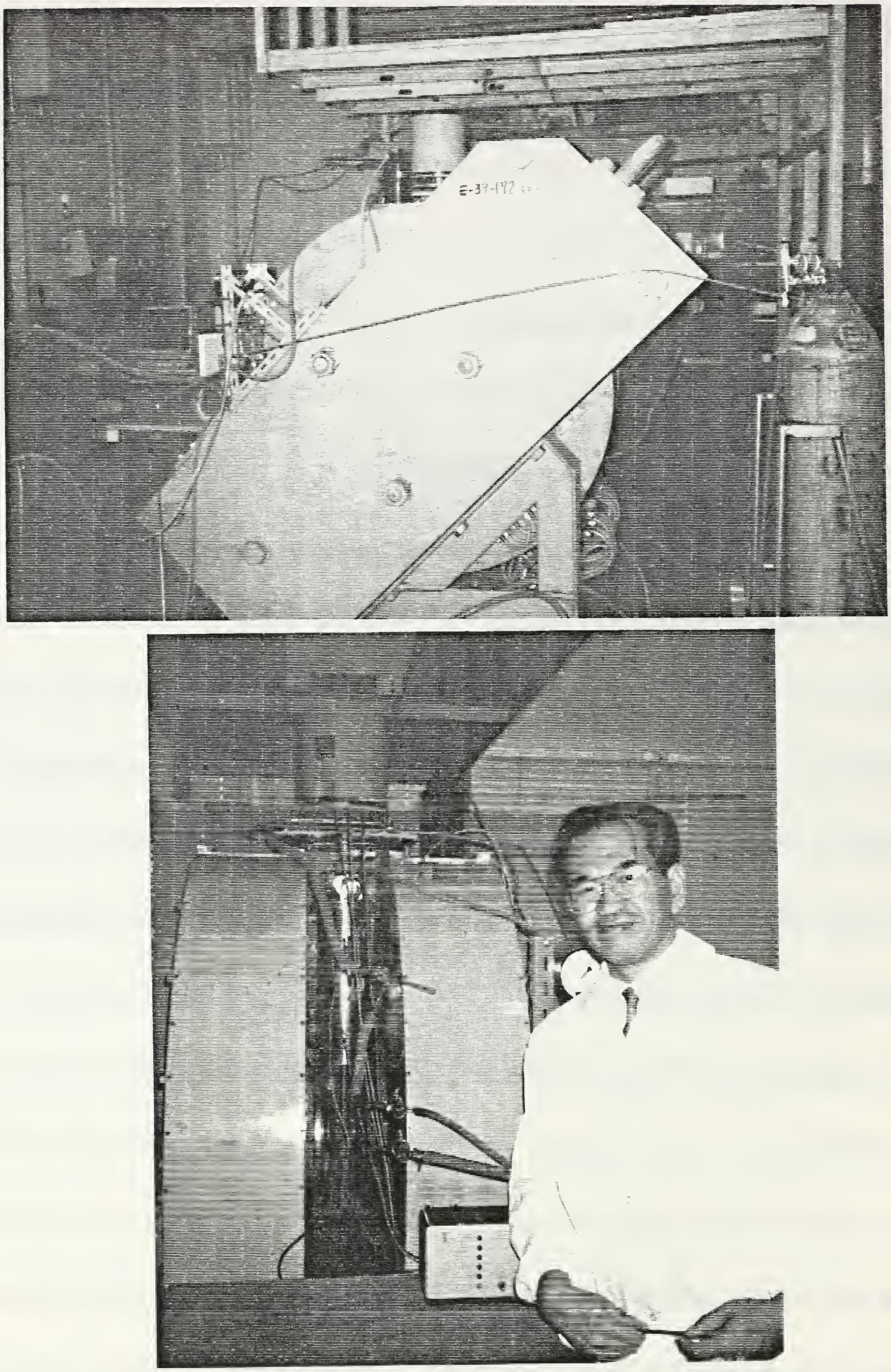
An effort at ISSP is also directed toward the generation of long-pulse (10 msec) fields by the methods of Foner[9] at the FBNML and Date[26] at Osaka University. For this purpose both a 200 kJ (5 or 10 kV, 16 or 4 mF respectively) and a 112 kJ (4 kV, 14 mF) capacitor bank are available[19]. Fields up to 54 Tesla (in a 15 mm bore) have been generated over a 10 msec time period. The conductor coil is made of either Cr-strengthened Cu or Cu wire containing embedded continuous multifilaments of Nb-Ti. For the latter wire, the Nb-Ti multifilaments comprise about two thirds of the cross sectional area and the wire has a thermal conductivity about two thirds that of pure Cu. By comparison, the Cu/Nb microcomposite wire (which contains short Nb filaments) developed by Foner et. al.[21] for this purpose is thought to be stronger, but has a lower thermal conductivity.

For all measurements, all data is measured and transmitted optically if possible in order to eliminate the shock hazard present when a conductor loop is located near a quickly changing magnetic field. For type II superconducting materials, the upper critical fields (H_{C2}) are determined by the maximum field excursion which still results in a spike in the

time derivative of the magnetization when the time derivative of the field changes sign. Outside individuals are requested to submit research proposals to ISSP for collaborative research.

E. TYPICAL MAGNET FACILITIES

For the typical Japanese laboratory investigating superconductors, the magnetic field facilities depend on the type of laboratory. Japanese government laboratories were the best equipped (both in terms of equipment age and capability). At NRIM (Meguro) there is a very large, 2.7 Tesla electromagnet (figure 13) and a couple "older" (1980 vintage) superconducting magnets (12 Tesla and 7 Tesla capability, manufactured by Oxford Instruments Inc. and JEOL Ltd. respectively) available for research in addition to the very high magnetic field facilities described earlier. At the Tsukuba NRIM facility, there are also several recently-constructed, high-field, general-purpose magnets available for research, including an 18 Tesla (1985), a 14 Tesla (figure 14), and a 7 Tesla (figure 14) submicron NbTi filamentary magnet. At the Electrotechnical Laboratory (ETL) are two rotatable superconducting magnets having split horizontal coils (5 Tesla maximum field) and a 4 Tesla vertical field coil used in the study of polymeric superconductors. In addition to 13 Tesla and 15 T superconducting magnets with $\sim$20 mm bores, ETL also has a 10 T magnet with a 200 mm bore and a 6 T superconducting magnet with a very large 400 mm bore available for research projects. At the International Superconductivity



(a)

(b)

Figure 13. 2.7 Tesla electromagnet viewed from (a) the side and (b) the front for measuring magnetization using the vibrating sample magnetometer shown mounted on top. Dr. Isao Nakatani (NRIM, Meguro) is standing next to the magnet in (b).

(a) (b)

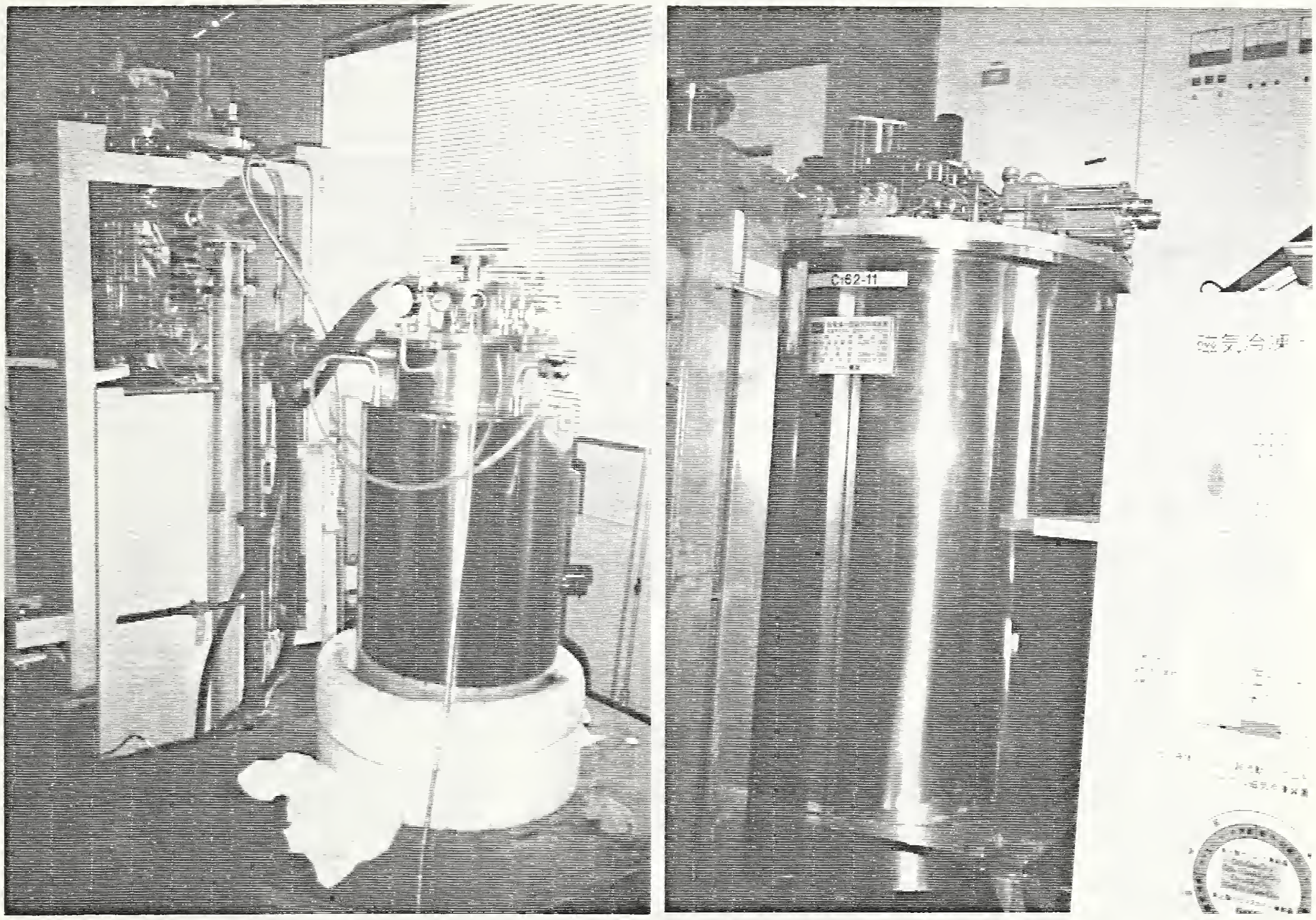


Figure 14. (a) 14 Tesla and (b) 7 Tesla superconducting magnets at NRIM (Tsukuba). The 7 Tesla magnet contains submicron NbTi filaments and can be cycled between zero and its maximum field with low losses.

Technology Center (ISTEC) the available facilities include a 15 Tesla (figure 15a) and an 8 Tesla (Oxford Instruments, figure 15b) high-homogeneity magnet as well as two, 5.5 Tesla systems using SQUID magnetometers (Quantum Design Inc., figure 15a) for susceptibility measurements.

(a) (b)

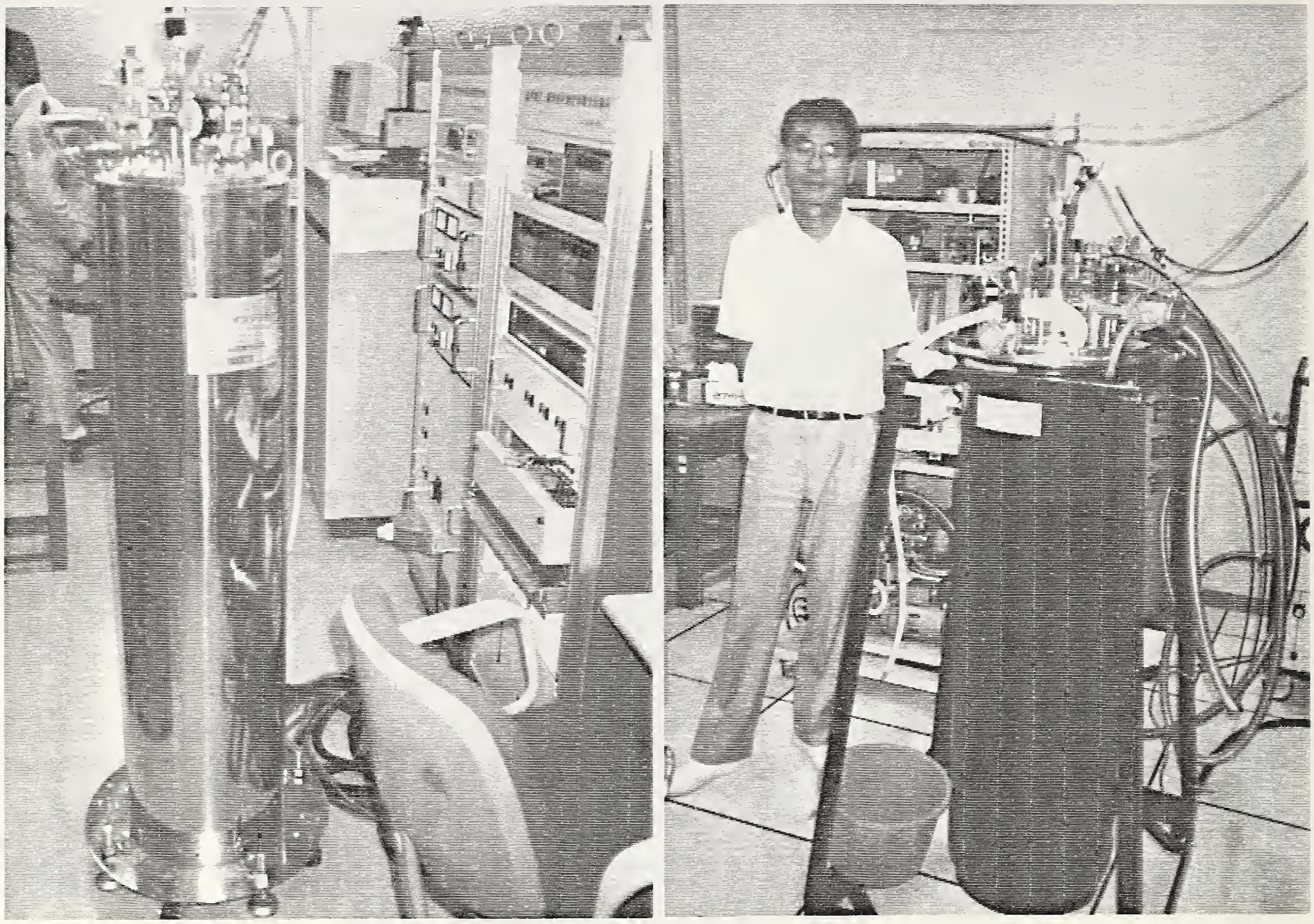


Figure 15. (a) 10 Tesla superconducting magnet (foreground) and a highly sensitive Quantum Design SQUID magnetometer (background) with a 5.5 Tesla superconducting magnet and (b) Dr. Satoshi Gotoh standing beside an 8 Tesla superconducting magnet for NMR measurements at ISTEC.

In comparison, non-government organizations are less well equipped with magnets. Sumitomo Electric Industries (Osaka), a leading superconducting cable manufacturer, has in-house magnetic field capability to only ~1 Tesla and a competitor Matsushita Electric Company (Osaka) similarly possesses only equipment to 1 Tesla (but including a high-resolution SQUID magnetometer). However, these companies have strong connections

with other organizations possessing the high-field facilities. For example, Sumitomo and Matsushita companies collaborate extensively with Professors Watanabe (Tohoku University) and Date (Osaka University) respectively. Nippon Telephone and Telegraph Company (Ibaraki), a 95% government-owned private company, however, possesses a 5.5 Tesla magnet combined with a Quantum Design SQUID magnetometer and also two large (Oxford Instruments) magnet systems for research: a 13.2 Tesla (50 mm bore) superconducting magnet and an 8 Tesla superconducting magnet for magnetoresistance measurements. The facilities at all the industries, however, for the preparation of superconducting materials in various forms are extensive.

At the universities, the equipment is much older and less abundant. Other than the hybrid magnets at Tohoku University (HFLSM), for instance, there is a 5 Tesla superconducting magnet with a SQUID susceptometer, a 12 Tesla resistive magnet with vibrating sample magnetometer attached, and a 15 Tesla superconducting magnet for magnetoresistivity data collection. At Osaka University (RCEM) no additional magnets were observed other than the pulsed-field facilities, and at the University of Tokyo (ISSP) similarly no steady field magnets were observed for complementing their pulsed-field research efforts.

III. SUPERCONDUCTOR PROPERTY MEASUREMENT

The superconducting properties which must be determined before a superconducting material can be utilized in any application are the values of T_C, H_C, and J_C and their interrelationships. H_C is usually measured by applying a magnetic field to the superconductor and noting the maximum field the material can tolerate without an electrical resistance being measurable. J_C is similarly determined as a function of magnetic field and temperature by noting the largest current that can be carried by the superconductor before it shows an electrical resistance at each field and temperature value. Figure 6 shows that for many of the commercially important superconductors H_C is very temperature dependent and its value can be very large at low temperatures. In fact, for Nb_3Al and Nb_3Ga there are presently no DC magnets (either resistive, superconducting, or hybrid) in the world which can apply magnetic fields as large as the critical fields of these materials at temperatures less than 4 K. Consequently, this data cannot presently be measured under static conditions. For Nb_3Ge and Nb-Ge-Al superconductors, H_C values cannot presently be measured at temperatures less than 8 K and 10 K respectively. Note from the discussion in section II above that most superconducting magnets are currently constructed of NbTi and a few from Nb_3Sn. From figure 6 it is obvious that existing field capabilities did not limit their characterization. The new superconducting oxides (La-Sr-Cu-O, Y-Ba-Cu-O, Bi-Sr-Ca-Cu-O, and Tl-Ba-Ca-Cu-O materials and their derivatives having T_C values greater than 25 K), however,

have critical fields much higher than those shown for the materials in figure 6, even at modest temperatures[30]. Consequently, much higher magnetic field facilities than presently available will be needed for their complete characterization.

A. CRITICAL FIELD AND CRITICAL CURRENT

The high magnetic field facilities in Japan are used extensively in superconductor research for primarily determining both the upper critical fields and the field dependence of the critical currents of these materials. In the past few years significant advances have been made as a result of these data. At Tohoku University (in collaboration with the Toshiba Company) improvements in the H_C (at 4.2 K) of NbTi materials by 2 Tesla upon the addition of tantalum or hafnium represents nearly a 20 percent improvement[24]. In addition, these ternary materials are more ductile than the binary NbTi alloy and, consequently, are easier to fabricate into wires. For multifilamentary superconductor wires, the Osaka Research Laboratory of Sumitomo Electric Industries found that critical currents could be significantly increased by reducing the size of each filament to less than 1 micron[31]. These wires also allowed the magnets to be used in an alternating current mode. A maximum J_C (at 1 Tesla applied field at 4.2 K) for a multifilamentary NbTi wire was found for a filament diameter of 0.07 μm. A process is now being developed by this laboratory for even making the higher H_C multifilamentary Nb_3Al superconducting wire[32]. Theoretical models are now being developed at the Electrotechnical Laboratory

to analyze the submicron filament size effects on the other magnet design criteria[33].

Research on the high T_C superconductors has shown that the application of a magnetic field not only shifts the resistive transition to lower temperatures (as in the lower T_C materials like NbTi), but also broadens it[34]. Consequently, there are three different criteria used by investigators for determining H_C (all based on the limiting value of the electrical resistivity below which the material is defined to be superconducting): (a) zero resistance, (b) the transition midpoint, and (c) 90% normal-metal resistivity. As in the United States, confusion in the literature values of H_C also exists in Japan due to their use of all three criteria as well. Two of the early findings about the new high T_C superconductors were the small values of critical current possessed by these superconductors and its strong decrease upon the application of a magnetic field[35]. Since these problems pose to be the major impediments to the application of these new materials, a great deal of effort is devoted in the Japanese research toward development of materials with improved critical current characteristics. New processes like the melt powdered melt growth (MPMG) method for making the $YBa_2Cu_3O_7$ superconductor[36] have been devised for increasing the flux pinning capabilities (and therefore the values of J_C) of the high T_C superconductors. In addition, a new method for observing the magnetic flux penetration through a superconductor by using the magneto-optical Faraday effect of a thin magnetic film deposited on top of the superconductor has been used at ISTEC[37] to help identify the nature and mechanism of flux trapping in the high T_C

superconductors. Especially noteworthy are the Ag-sheathed BiPbSrCaCuO superconductors (T_C values around 104 K) prepared by Sumitomo Electric Industries[38]. These materials are formable into tapes which can be easily bent[39] and can possess relatively high values of J_C (figure 16). At 4.2 K figure 17 shows J_C is not very anisotropic. This figure also shows the Ag-sheathed BiPbSrCaCuO superconductor is even relatively insensitive to H for field values up to 20 Tesla at 4.2 K. At 77 K, however, a field dependence develops for $H > 1$ Tesla (figure 18) as well as a crystallographic anisotropy in J_C. For comparison, the J_C-H regions possessed by the commercial NbTi and Nb_3Sn superconductors are also shown in figure 17. The Ag-sheathed BiPbSrCaCuO superconductor also possesses J_C values which are much less stress dependent than those of Nb_3Al (a low T_C superconductor, desirable partially because of its insensitivity to mechanical stress conditions). Wires of this high T_C material are now being marketed for use as the current leads in superconducting magnets since these wires can easily be kept cooled well below its T_C of 92 K by the free venting of vaporized liquid helium. Wires of relatively flexible thin ribbons of BiSrCaCuO have also been prepared by a "modified doctor blade" process (figure 19) developed at NRIM[40].

For obtaining critical field values in excess of 30 Tesla, measurements need to be obtained using pulsed-field facilities[30]. For type II superconductors, a discontinuity will occur in the field dependence of the magnetization when the direction of field change is

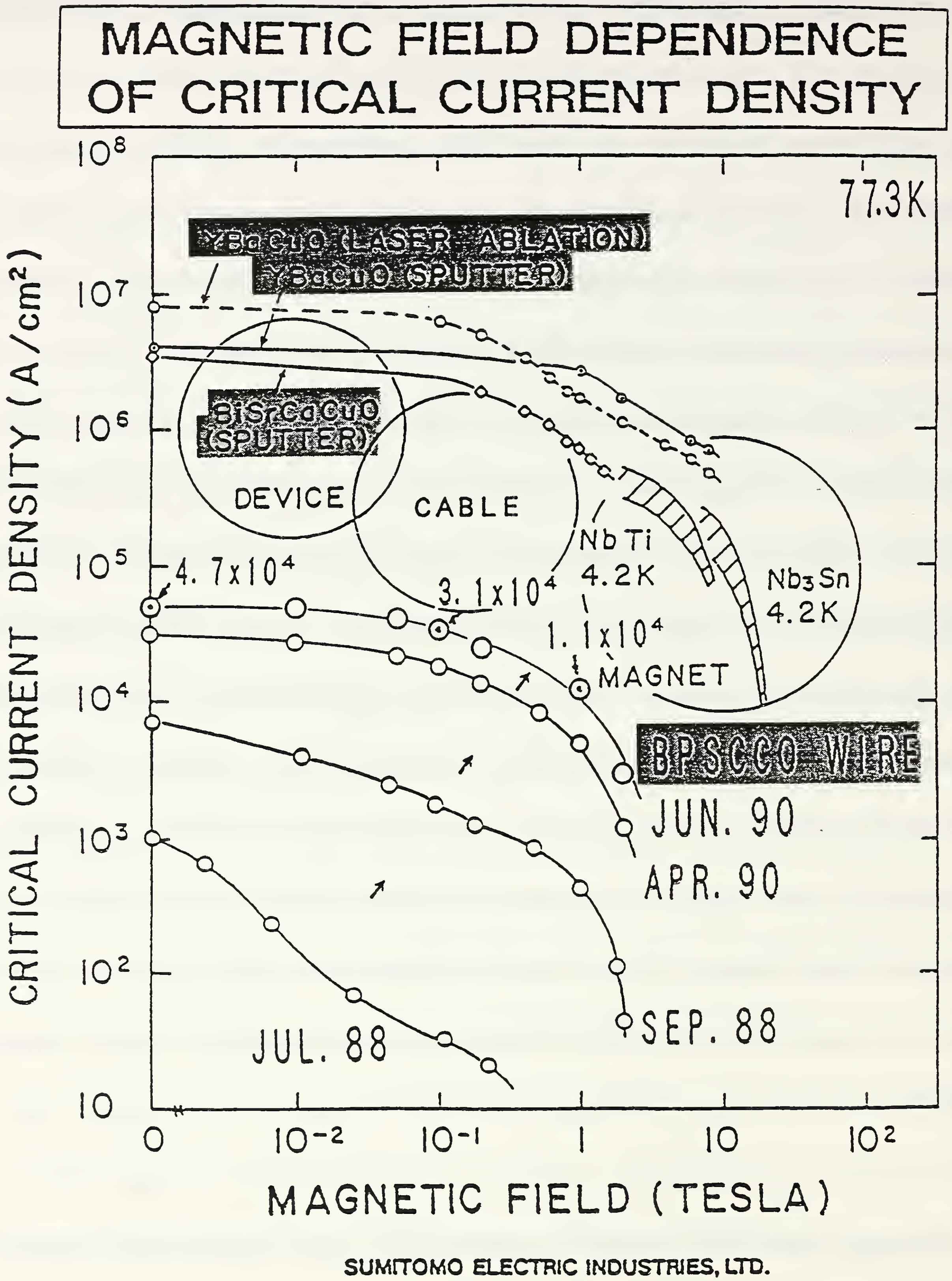


Figure 16. Critical current density versus date achieved at the indicated magnetic fields for Ag-sheathed BiPbSrCaCuO high T_c superconductors developed by Sumitomo Electric Industries, Ltd.

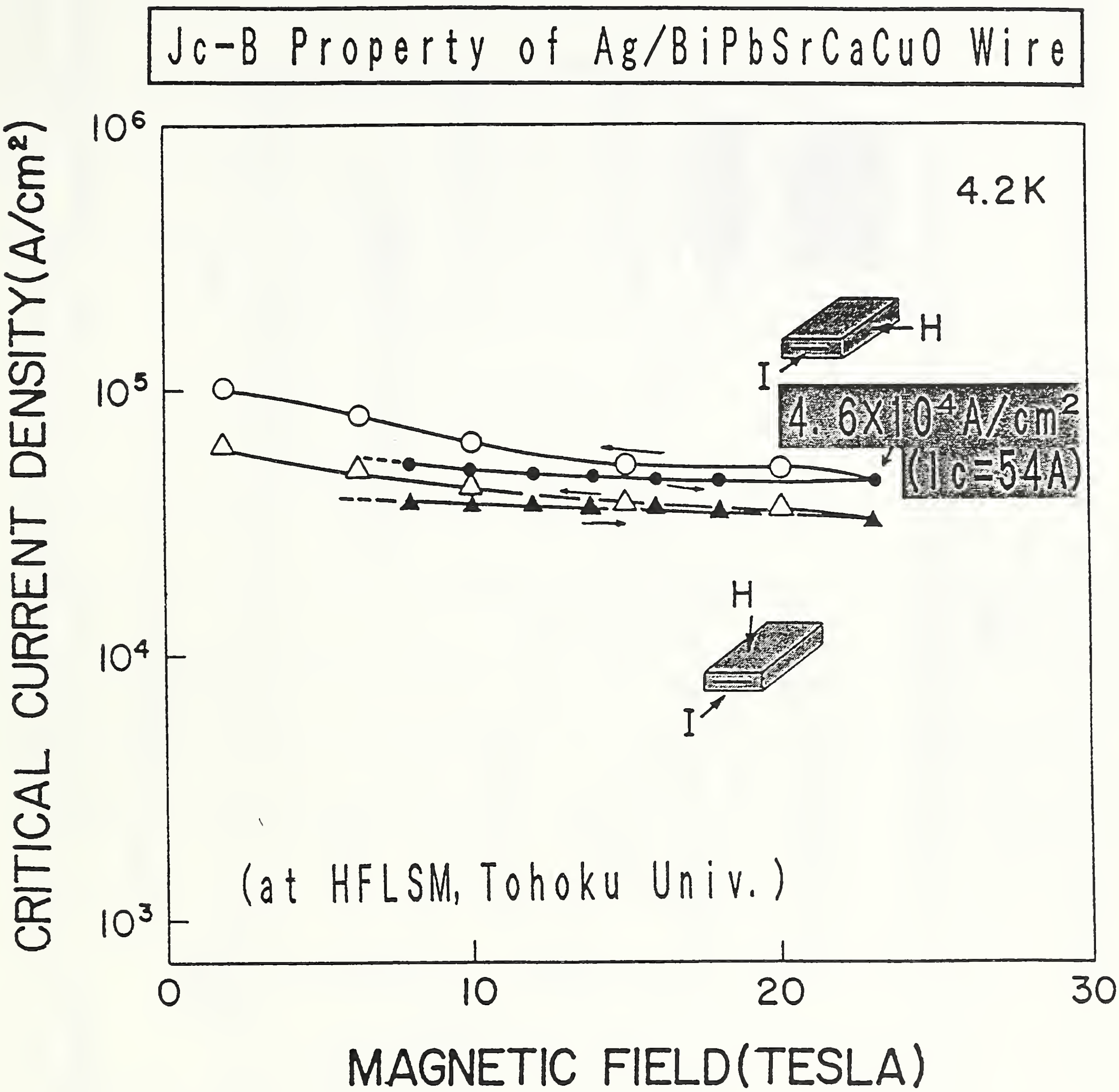


Figure 17. Magnetic field dependence of the critical current density at 4.2 K for Ag-sheathed BiPbSrCaCuO superconducting wire made by Sumitomo Electric Industries, Ltd. measured with the field, H, parallel (circles) and perpendicular (triangles) to the wide dimension of the tape as indicated.

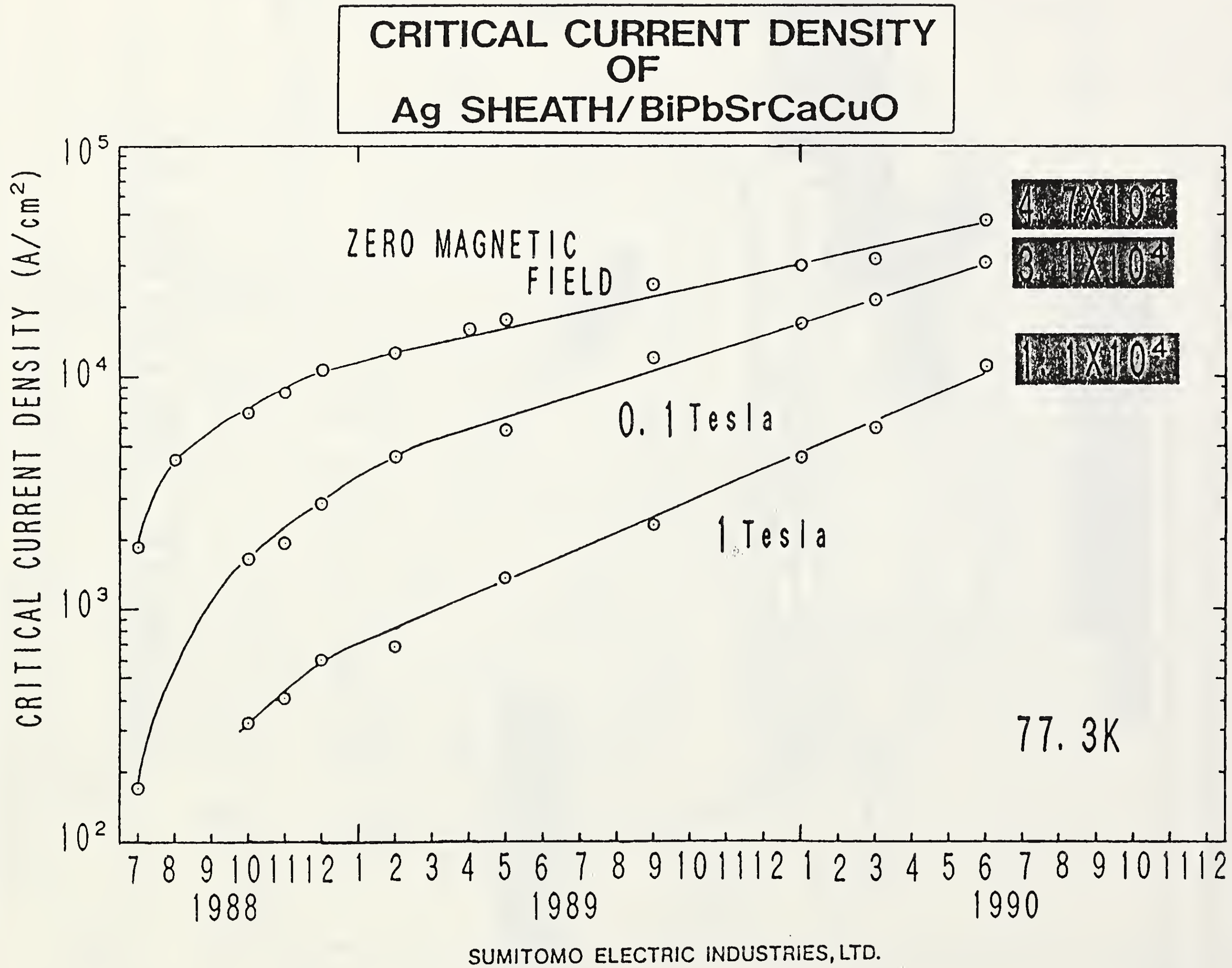
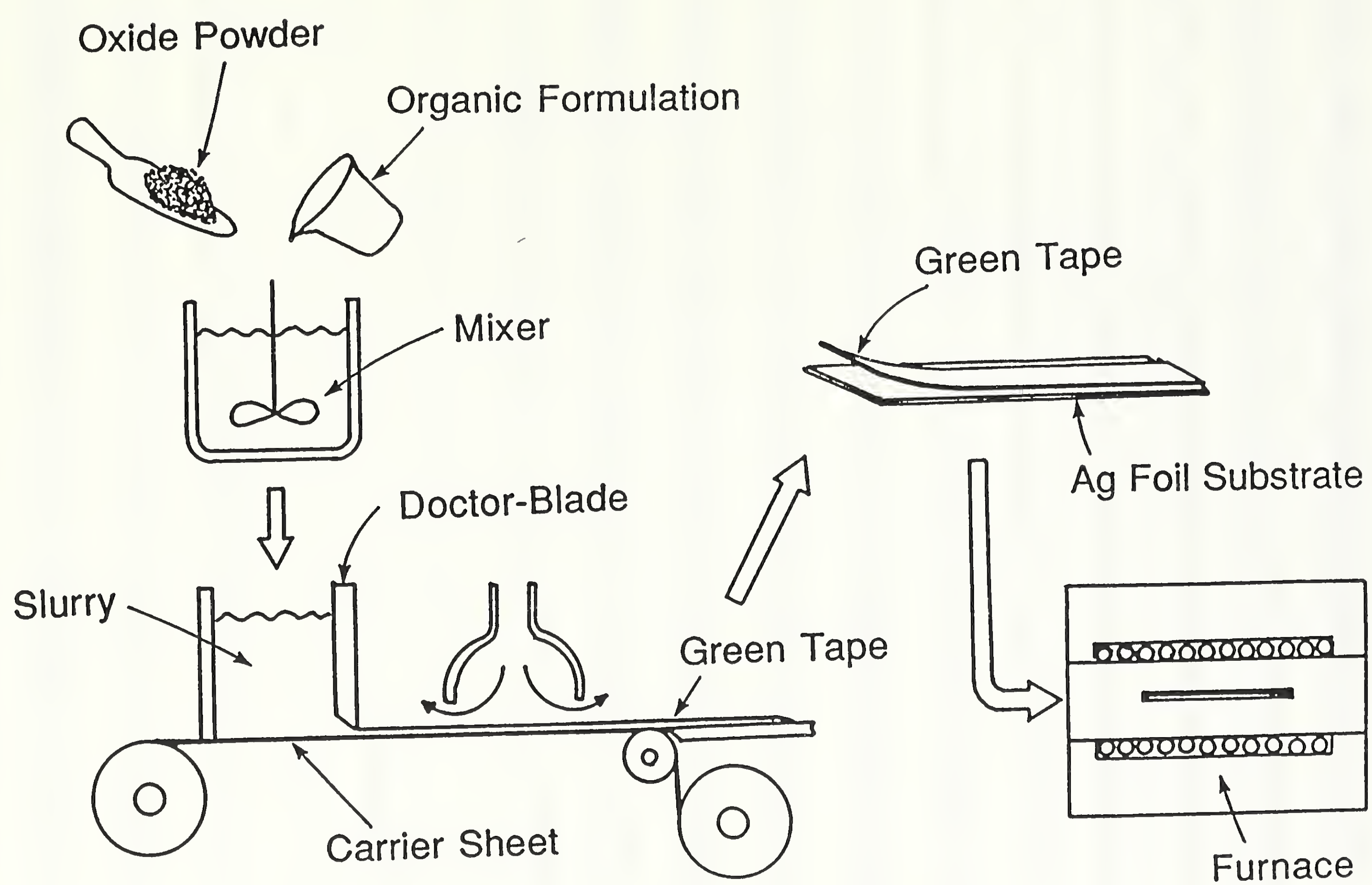


Figure 18. Magnetic field dependence of the critical current density at 77.3 K for three Ag-sheathed BiPbSrCaCuO superconducting wires developed at the indicated dates by Sumitomo Electric Industries, Ltd. For comparison, the data for YBaCuO and BiSrCaCuO thin films and both NbTi and Nb_3Sn wires (at 4.2 K) are also shown.



Schematic drawing of the sample preparation.

Figure 19. Schematic of the roller-containing "doctor blade" process developed at NRIM for preparing relatively flexible thin tapes of the Bi(Pb)-Sr-Ca-Cu-O high-T_c superconductor.

reversed (as it is at the maximum applied field). The maximum applied field for which such a discontinuity in the M vs H data is observed is a measure of the critical field for the superconductor. Because many pulsed-field measurements (each with a different maximum field) are required for such an H_C determination, non-destructive facilities are necessary. Consequently, both the facilities at ISSP (University of Tokyo) and at RCEM (University of Osaka), in addition to the facilities at the FBNML (Massachusetts Institute of Technology), are utilized by Japanese researchers for these measurements[41]. H_C values determined by pulsed techniques, however, are usually higher than those determined from constant field measurements, probably because of the time required for magnetic flux lines to enter and leave the superconductor. During pulsed-field applications equilibration of the magnetic flux lines is not possible. For many of the high T_C superconductors, the flux dynamics also vary with the magnetic field strength, changing from flux diffusion to flux creep and even to flux "melting" regimes[42].

B. MAGNETIC RESONANCE

In order to understand the basic mechanisms underlying the superconducting state in the various types of superconductors, magnetic resonance experiments provide important information. Higher resolution is obtained in Nuclear Magnetic Resonance (NMR) data when the higher magnetic fields are used. Such measurements can identify site occupations for various atomic species (like oxygen or copper in the high T_C

superconductors) and provide information on the electric field gradients present in various locations of the material. With the new broad band 16 Tesla NMR magnet recently installed at NRIM (with a field homogeneity of 10^{-5}) the initial tests resulted in much narrower NMR peak widths than some of the best data in the world measured earlier (figure 20). At NRIM a present effort is directed toward the observation Cu atoms in the almost superconducting compound $YBa_2Cu_3O_6$ (which is antiferromagnetic). Of interest is how the electric field gradient near the Cu atoms located on the "chain" sites varies with temperature and field, and how it compares to the gradient near the same atoms in the related superconducting $YBa_2Cu_3O_7$ compound. In order to understand the role of the Cu-O bond (if any) in creating the superconducting state in the high T_C superconducting oxides (almost all of which contain Cu and O) electron spin resonance (ESR) experiments are being performed using the very high field facilities of RCEM (Osaka University)[43]. Normally, ESR data is measured at microwave frequencies. However, since the ESR frequency is proportional to the applied magnetic field, the experiments at RCEM are being performed in the submillimeter wavelength region using HCN (337 μm wavelength) and H_2O (119 μm wavelength) lasers. The results indicate that CuO might have a multisublattice structure even at low temperatures.

C. OTHER PROPERTIES

Other measurements which require the use of high magnetic fields include the de Haas-

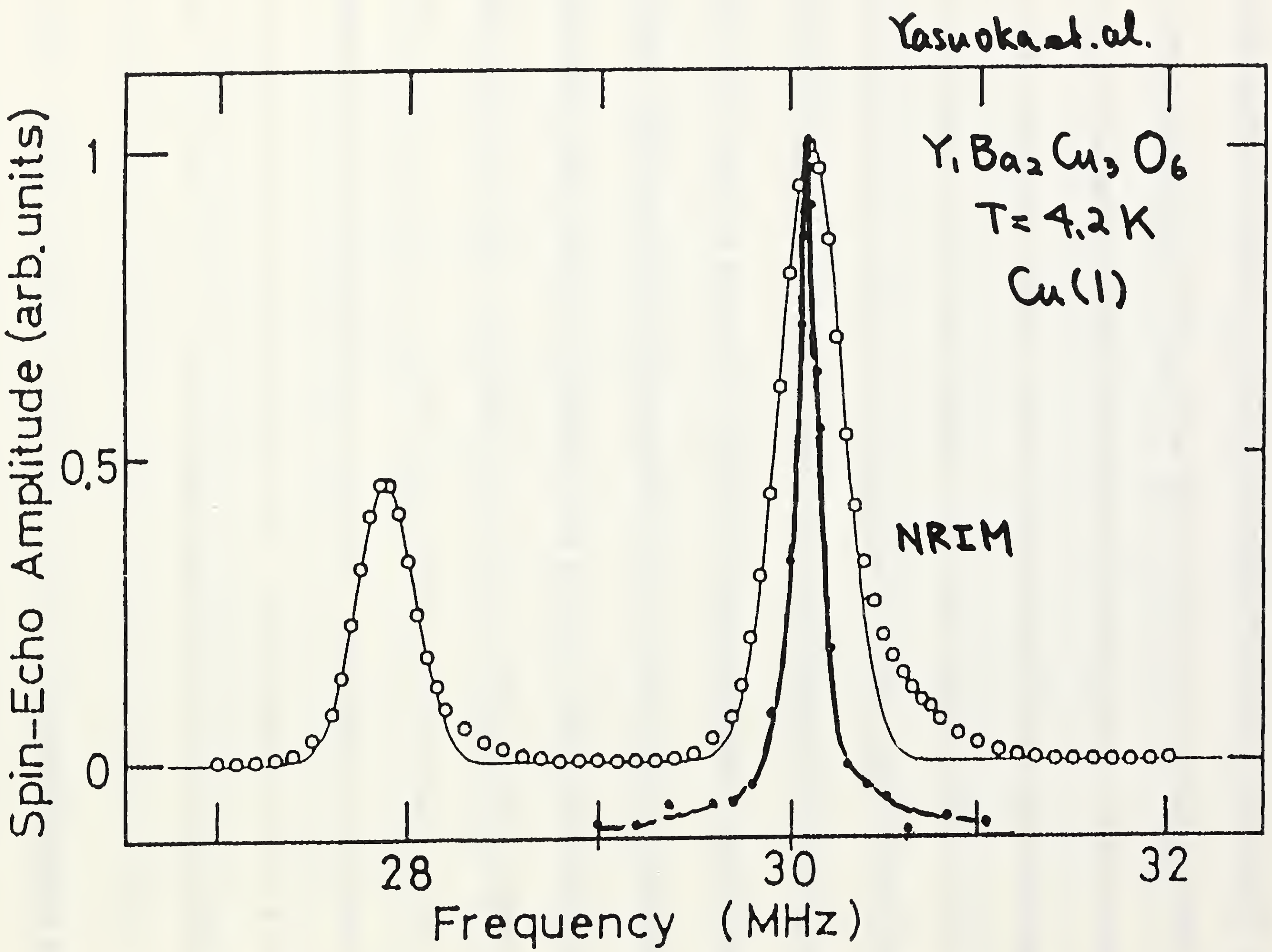


Figure 20. Nuclear Magnetic Resonance data measured at 4.2 K for $YBa_2Cu_3O_6$ using NRIM's new high field homogeneous magnet (filled circles)[49] and measured elsewhere (open circles). The much narrower peak in the NRIM data shows the high resolution of the NRIM equipment.

van Alphen (dHvA) effect experiments. Such data, for example, can help determine whether or not the high T_C superconducting oxides are "metallic". In this experiment, a search is made for quantum oscillations in the material proportional to 1/H (where H is the magnetic field). Efforts are presently underway at NRIM (Meguro) and at ETL to make such measurements. The only results so far are those of Max Fowler (Los Alamos National Laboratory)[44] which indicate the high T_C superconductors are metallic and possess a fermi surface. The magnetic fields required for observation of the oscillations were also smaller than expected. In order to map out the fermi surface of the material many sample orientations with respect to the magnetic field are required. Rotatable magnets, such as those specially designed at ETL, would be especially useful for such studies. A complementary method being promoted at ETL is the Shubnikov-de Haas effect. This method has been used at ETL to investigate polymeric superconductors[45] but needs higher field capability (10 Tesla minimum) to study the high T_C superconducting oxides.

The Hall effect also provides information on the fermi surface of the superconductors. In this technique a magnetic field is applied perpendicular to an electric current through the sample and the voltage in the third orthogonal direction is measured. At ETL a great deal of effort on polymeric superconductors[46] has shown that these materials are "metallic", possess positive Hall coefficients, and possess relatively temperature-independent hole numbers. In addition, the electrical resistivity data of these materials

suggests metallic behavior by their positive temperature dependences when in the "normal" state. Research on these materials is also in progress at ISTEC[47].

In order to understand the superconducting state in the high T_C superconductors a number of additional experiments have been conducted at Osaka University at high fields. The first involved the measurement of magnetization of CuO at high fields[48] since the magnetic coupling between Cu spins via oxygen atoms is believed to be important to the superconducting mechanism in the superconducting oxides. It was found that CuO could be regarded as a one-dimensional magnet where frustration effects are expected between Cu-O-Cu chains. In $NdCuO_4$, a non-superconducting oxide structurally related to the high T_C superconductors, a sequence of spin canting and direction switching of the Cu spins was detected as the magnetic field was increased. This indicates strong magnetic interactions exist between the Cu spins in the system. At magnetic fields larger than the critical field the electrical resistivity of several high T_C superconductors was measured and was found to follow metallic behavior, thereby supporting conclusions from Hall Effect data and zero-field electrical resistivity data at temperatures above T_C.

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This report is written in partial satisfaction of the requirements of the Japanese Technical Literature Act of 1986, Public Law 99-382 (Aug. 14, 1986). This law requires the Secretary of Commerce to prepare annual reports on the important scientific discoveries and technical innovations in certain important identified areas such as computers, semiconductors, biotechnology, robotics, and manufacturing. This report on the magnetic field facilities in Japan for conducting research on superconducting materials is a result of a trip to various locations in Japan between August 22, 1990 and September 1, 1990 by Dr. Robert D. Shull, a prominent researcher in both magnetism and superconductivity at the National Institute of Standards and Technology. For comparison to U.S. Capabilities, Dr. Shull also made trips to the Francis Bitter National Magnet Laboratory at MIT and to the Los Alamos National Laboratory respectively before and after the Japanese trip. The organizations visited in Japan included the High Field Laboratory for Superconducting Materials (HFLSM) at Tohoku University, Osaka University, Sumitomo Electric Industries Ltd. Matsushita Electric Co. Ltd., NRIM at Meguro, NRIM at Tsukuba, ETL, ISTEC, Nippon Telephone and Telegraph Co. at Ibaraki, and ISSP at the University of Tokyo.

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